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POLICY PAPER

Measuring What Matters: An Integrated Framework for Assessing Land Use Outcomes

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Abstract: Land is a multifunctional resource critical to agriculture, forestry, biodiversity conservation, ecosystem services, bioenergy production, and cultural and recreational uses. However, achieving optimal land use outcomes requires policy frameworks grounded in robust evidence. This study reviews existing land use assessment models to inform the development of an integrated framework for evaluating policy-driven land use outcomes. We arrive at a list of 36 priority indicators to support strategic governance, rural development, and long-term environmental resilience. We use Ireland as a case study which reveals critical data gaps and underscores the importance of investment in data infrastructure to support evidence-based decision-making.

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I INTRODUCTION

Land, the focus of this study, is a multifunctional resource that supports national output through agriculture and forestry, sustaining biodiversity, providing ecosystem services such as climate and water quality regulation, bioenergy production, and offering recreational and cultural opportunities. The benefits of a well-managed landscape collectively enhance human well-being while protecting the environment for future generations. Developing a deeper understanding of land use outcomes can inform the adaptation of land use policies to improve environmental health, resource availability, food, fibre, fuel production, and broader socio-economic outcomes.

The objective of this study is to develop a list of priority indicators that offer a multifunctional perspective on land use, accounting for both direct and indirect impacts as recommended by De Rosa (2018). The list of indicators is refined to enhance the feasibility of data collection on a frequency and granular level. Therefore, the contribution made by this research to supporting evidence-based decision-making is two-fold; it is a review of existing national and international land use assessment frameworks, and it develops an integrated framework to comprehensively assess land use policy-driven outcomes. In doing this, we create a tiered system of indicators so that a poor performance in a summary indicator can be tracked by a diagnostic indicator.

The feasibility of the assessment framework is evaluated through a case study of the Republic of Ireland (henceforth Ireland), identifying data availability and collection gaps. This analysis is particularly valuable as Ireland is assessing its capacity to monitor land use-driven changes, e.g. the *Land Use Evidence Review* (O'Rourke *et al*., 2023). Ireland presents an interesting case study as it falls short of meeting several environmental targets, including greenhouse gas and ammonia reduction commitments (Environmental Protection Agency, 2024g). It also has the highest proportion of land allocated to agriculture in the European Union, covering 69 per cent of the total land area, primarily as grassland, followed by forestry (11 per cent), wetlands (7 per cent), and settlements (2 per cent) (Central Statistics Office, 2023a). Additionally, the development of land use assessment indicators was specifically recommended in Phase 1 of the *Land Use Evidence Review*.

Headline national statistics such as conventional measures of national economic performance provide an important but incomplete perspective on land use outcomes. Three commonly used national output indicators, usually in per capita terms, are Gross Domestic Product (GDP), Gross National Income (GNI), and Gross National Product (GNP). GDP measures the total value of goods and services produced within a country's borders, including foreign income. In contrast, GNI measures income from residents and businesses domestically and abroad, excluding income earned by foreign entities within the country. GNP is similar to GNI but includes net income from abroad. In practice, GNI and GNP tend to be nearly identical, while GDP is substantially inflated in Ireland due to the presence of unintegrated multinational corporations. Subsequently, GNI is the normal basis for measuring economic output in such cases. It is recommended that, at a minimum, companion metrics such as subjective well-being and wealth measures supplement these indicators (Stiglitz *et al*., 2010). Inequality-adjusted measures such as Equally Distributed Equivalent (EDE) income (Atkinson, 1970) are also increasing in popularity, including the value of public goods and services, though requiring a substantially greater information burden (Gethin, 2023).

National land use policy in Ireland is also guided by objectives spanning food, fibre and fuel production, climate mitigation and adaptation, water quality protection, biodiversity conservation, and spatial planning, among others. These objectives are embedded in a range of sectoral and cross-cutting policy frameworks and management plans. Correspondingly, a wide array of indicators is collected and reported by disparate sources, particularly where required to meet domestic, European Union, and wider international regulatory and reporting obligations. These include greenhouse gas emissions inventories, ammonia and nutrient monitoring, water quality status, Common Agricultural Policy implementation metrics, and protected area reporting. Land use outcomes are also shaped by budgetary, institutional, legal and social constraints, including planning and licensing processes, landowner participation and administrative capacity. The central challenge for monitoring, therefore, is not the absence of indicators, but the fragmented manner in which existing indicators are collected, reported, and linked to policy objectives. This motivates the need for a structured assessment framework that builds on what is already measured while improving on availability of the most relevant indicators as a basis for policy development and assessment.

The extent of agricultural production, forest redevelopment and energy production – including energy crops, feedstock for anaerobic digestion and solar farms (non-exclusive) presents opportunities as well as challenges, as nations work to meet their extensive environmental and social targets. Many objectives can be framed in terms of working towards the European Green Deal, climate action, and promoting economic growth (European Commission, 2019). Complementary to this, Ireland's National Energy and Climate Plan (NECP) outlines strategies for renewable energy expansion and emissions reductions across key sectors (Department of the Environment, Climate and Communications, 2024). Other commitments include adherence to the United Nations Sustainable Development Goals and policies to halt biodiversity loss, such as Ireland's National Biodiversity Action Plan (Department of the Environment, Climate and Communications, 2022a; 2022b; National Parks and Wildlife Service, 2024). These frameworks highlight the need for integrated land use management that balances production, sustainability, and socio-economic progress.

Beyond meeting national and international commitments, land use policy is essential for sustainability, resource availability, socio-economic performance, and resilience. Effective policy requires a strategic mix of regulations, investments, and incentives to promote sustainable management. These may include price-based mechanisms for efficient land use while safeguarding conservation areas and ecosystem services. Rural economic development strategies could enhance employment, public goods provision, and resilience to environmental and economic shocks. Additionally, policies could support sustainable food systems and bioenergy development. Strengthening governance and investing in research-driven land management will ensure that land remains a valuable asset. However, such efforts require sufficient data to monitor land use policy outcomes. Reliable, high-resolution data are essential to evaluate the effectiveness of policies, identify emerging challenges, and refine strategies to ensure sustainable and equitable land use management. This analysis helps build that basis.

The remainder of this paper is structured as follows: First we outline the process of collecting and condensing indicators from existing assessment frameworks and selecting key summary indicators. Then we examine and organise the condensed indicator dataset, focusing on the information it provides for the assessment model. During that stage, we present our findings on data availability in our case study of Ireland. Finally, we conclude with insights on transitioning from this review to an operational assessment model through improved data collection and coordination.

II MATERIALS AND METHODS

With a view to developing a robust and policy relevant assessment framework for land use in Ireland, we adopt a staged methodological approach. First, we characterise the institutional landscape of land use governance in Ireland as it stands, and decide on a set of outcome-based policy categories which reflect Ireland's current reform agenda.

We then draw on a wide range of established expert-based indicator sets to assemble an initial pool of candidate indicators capturing food, fibre, and fuel production, as well as environmental and socio-economic outcomes. Using established indicators allows us to incorporate multiple perspectives and to build on the expertise embodied in previous research. In addition to comprehensive indicator sets, we include a small number of key standalone indicators that serve as aggregate based measures providing summary depictions of the state of, for example, nature.

We present and discuss the sources of candidate indicators drawn from international and national frameworks. This includes identifying both comprehensive indicator sets and standalone summary indicators, as reported in Table 1. Then, we describe the methodology for refining this broad set of candidates to a small number of indicators relevant for assessing land use policy impacts. This involves harmonising terminology, prioritising indicators that are likely to change in response to land use policy and applying a structured vote-based approach. Afterwards, we present our resulting tiered assessment framework.

2.1 The Land Use Governance Landscape

To develop an integrated framework for monitoring land use change, we first characterise existing land use regulation and policy objectives in Ireland. Land use regulation has traditionally been characterised by a multi-tiered, multilayered governance structure. Recently, however, there has been a push for a modernised and more unified approach to land use governance (Government of Ireland, 2024a). We find it useful to first categorise land use regulation and policy objectives as they stand, then re-bundle them into overarching categories which might instead be jointly managed.

At the core of Ireland's spatial planning and zoning has been a series of Planning and Development Acts from 2000 to 2024 (Government of Ireland, 2000; 2024a) which then trickle down through levels of government through the National Planning Framework (Government of Ireland, 2025), Regional Spatial and Economic Strategies, and local authority Development Plans. The plans regulate zoning for residential, commercial, industrial, agricultural and conservation uses of land and guide planning permission decisions. In addition to the planning system there is an extensive body of environmental and conservation-focused land use regulations which are primarily the result of European Union law. These include Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) designated under the Habitats and Birds Directives (Council Directive 92/43/EEC; Directive 2009/147/EC), Natura 2000, and the designation of Natural Heritage Areas, primarily administered by the National Parks and Wildlife Service. Such designations impose legally binding constraints on land use that apply irrespective of zoning objectives.

Agricultural and other land uses are primarily regulated outside the statutory planning system as well through sector-specific regulatory frameworks. Agricultural land use is shaped by the Common Agricultural Policy, including Good Agricultural and Environmental Condition standards and nitrates regulations (Council Directive 91/676/EEC; Government of Ireland, 2022), administered by the Department of Agriculture, Food and the Marine and the Department of Housing, Local Government and Heritage. Land use in Ireland is constrained by several cross-cutting regulations related to air, water, climate and risk management. River Basin Management Plans under the Water Framework Directive impose requirements on land management within catchments (Directive 2000/60/EC). Climate policy has also become an increasingly important de facto land use regulator, including through peatland protections and rewetting initiatives, renewable energy planning and carbon-related land management measures (Government of Ireland, 2015). Regulatory functions in this area are primarily overseen by the Environmental Protection Agency and the Office of Public Works.

As there has been a push for Ireland to move towards a more unified approach to land use management, we categorise regulations and policy aims into outcome-based categories. These are intended to provide a coherent analytical structure for monitoring land use change and policy effectiveness across domains that are currently governed separately. We begin with air, soil, and water as foundational environmental domains, reflecting the biophysical systems within which activities occur. We then distinguish biodiversity and climate change as crosscutting environmental objectives of particular policy urgency, based on Ireland's legally binding commitments and the strong spatial footprint of mitigation, adaptation, and conservation measures. Finally, we include production and socioeconomic outcomes to reflect the role of land use policy in accommodating food, fibre and fuel production, housing, infrastructure, employment, and broader societal needs.

The outcome-based categorisation reframes land use zoning and sector specific regulation as instruments in service of multiple, potentially interacting objectives. In this framework, zoning is treated as a coordinating tool through which trade-offs between, say, environmental protection, climate action, and productive land uses are mediated. Bundling indicators by objectives allows for a clearer assessment of where policy goals are aligned and where monitoring gaps exist. The approach should facilitate joint management through integrated monitoring from all relevant agencies to support the shift towards more coherent land use governance. The following section applies this outcome-based categorisation to develop and assess a structured set of land use indicators for Ireland.

2.2 Indicator Sources

The sources of candidate indicators are reported in Table 1. Phase 1 of the *Land Use Evidence Review* (O'Rourke *et al.*, 2023) served as the foundation for our dataset, proposing a broad array of indicators in Appendix A of *Indicator Assessment* (Byrne and O'Rourke, 2023). That report compiles over 300 indicators across various domains, including those specific to Ireland. Sources of Phase 1 indicators include the Aichi Biodiversity Targets, Ireland's National Biodiversity Indicators, the European Environment Agency (EEA), the United Nations Sustainable Development Goals Programme (UN SDG), Ireland's National Parks and Wildlife Service (NPWS), Ireland's Environmental Protection Agency (EPA), the International Union for Conservation of Nature (IUCN), BirdLife International, and the National Biodiversity Data Centre (NBDC). While comprehensive, the report was explicitly preliminary, encouraging subsequent refinement and prioritisation of indicators for practical application. However, tracking over 300 indicators in practice is challenging due to the administrative workload required to do this on a granular and frequency basis, across many agencies. Our work addresses this limitation by first expanding the scope of exploration and then narrowing the number of indicators through an 'expert vote' approach to refine the list to those which data collection could be prioritised. Indicators appearing in multiple assessment frameworks receive greater consideration for inclusion to ensure that the resulting integrated framework will be widely applicable.

We then add indicators related to the 17 United Nations' SDGs adopted by all member states in 2015. These address several social and environmental issues as an update to the Millennium Development Goals (MDGs) by broadening them to encompass challenges faced by both developed and developing nations (United Nations 2023; 2024). We added The Human Development Index (HDI) composite, which focuses on SDG goals on health, education, and income, recently enhanced by 'planetary pressures' adjustments to factor in CO_2 emissions and resource use (United Nations Development Programme, 2024). The UNDP's inequality-adjusted HDI, the IHDI, further factors in intra-country inequality using a national inequality aversion parameter following the work of Atkinson (1970). An alternative approach would be to use the SDG Index, which is currently based on 125 indicators, but the 0 to 100 scoring system does not weigh trade-offs between progress and setbacks across indicators (Sachs *et al.*, 2024).

The European Commission's Common Agricultural Policy (CAP) includes a Performance Monitoring and Evaluation Framework (PMEF) for 2023-2027 (updating from CMEF in 2014-2022) composed of 44 result and 47 general context indicators (European Commission, 2024). Complementing CAP, Ireland's Central Statistics Office (CSO) Environmental Performance Indicators (CSO-EPI) focus on land use impacts with 70 indicators aligned with CAP's objectives but providing localised environmental metrics (Central Statistics Office, 2023a).

Mapping and Assessment of Ecosystems and their Services (MAES) provides 202 indicators (Maes *et al.*, 2020), following recommendations in the Millenium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005) and indicator development (Layke *et al*., 2012; Parker *et al*., 2016). The MAES indicators tend to be habitat specific and are further divided into pressures on, and conditions of, ecosystems. This supports diagnostic work by distinguishing between the observed states of ecosystems and the pressures that are driving changes in their status. However, ecosystem services measurements will require substantial customisation to be actionable. This is because ecosystem service values are easier to define and measure in principle than in practice. They tend to be based on not just the ecosystem and service it provides, but also on who benefits from the service. As such, two sites can produce different levels of value even if they provide a similar service but are situated in communities with different levels of dependency on nature. Ecosystem services usually also have public goods attributes such as being difficult to make exclusive, which further complicates their measurement. Therefore, the measurement of ecosystem services – even which services to measure – requires tailoring. Even so, the approach of viewing the environment as a provider of several sources of value has gained in prominence since its origin in the 1970s (Gómez-Baggethun *et al*., 2010), and should be considered as a means of incorporating the value of nature in budgeting decisions.

Table 1: Models of Assessment Indicators

Category	*Focus*	*Number of Indicators*
Models of indicator sets		
Phase 1 of the *Land Use Evidence Review* [1]	Broad, guided by land use outcomes	300+
Sustainable Development Goals (SDGs) [2]	Broad (social, economic, environment)	249
Human Development Index (HDI) [3]	Socio-economic development	5-7
Common Agricultural Policy (CAP) [4]	Agriculture and rural development	91
CSO Environmental Performance Indicators (CSO-EPI) [5]	Socio-economic and environmental	70
Mapping and Assessment of Ecosystems and their Services (MAES)[6]	Ecosystem services	202
Convention on Biological Diversity (CBD) - Aichi Targets [7]	Biodiversity conservation	162
Ireland's National Biodiversity Action Plan (NBAP) [8]	Conservation plan implementation	50+
Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) [9]	Biodiversity conservation and ecosystem services	71
Ireland's Climate Change Assessment (ICCA) [10]	Climate change adaptation	Varies
Sendai Framework for Disaster Risk Reduction (SFDRR) [11]	Disaster risk management	7
Environmental Vulnerability Index (EVI) [12]	Environmental risk	50
INFORM Index for Risk Management [13]	Disaster risk management	Varies
Environmental Performance Index (EPI) [14]	Environment and human health	58
Global Competitiveness Index (GCI) [15]	Economic performance	64
Global Peace Index (IEP-GPI) [16]	Security	23
Ecological Threat Report (ETR) [17]	Environmental and societal threats	4
Stockholm Resilience Centre (SRC) Planetary Boundaries [18]	Environmental stability	7 of 13

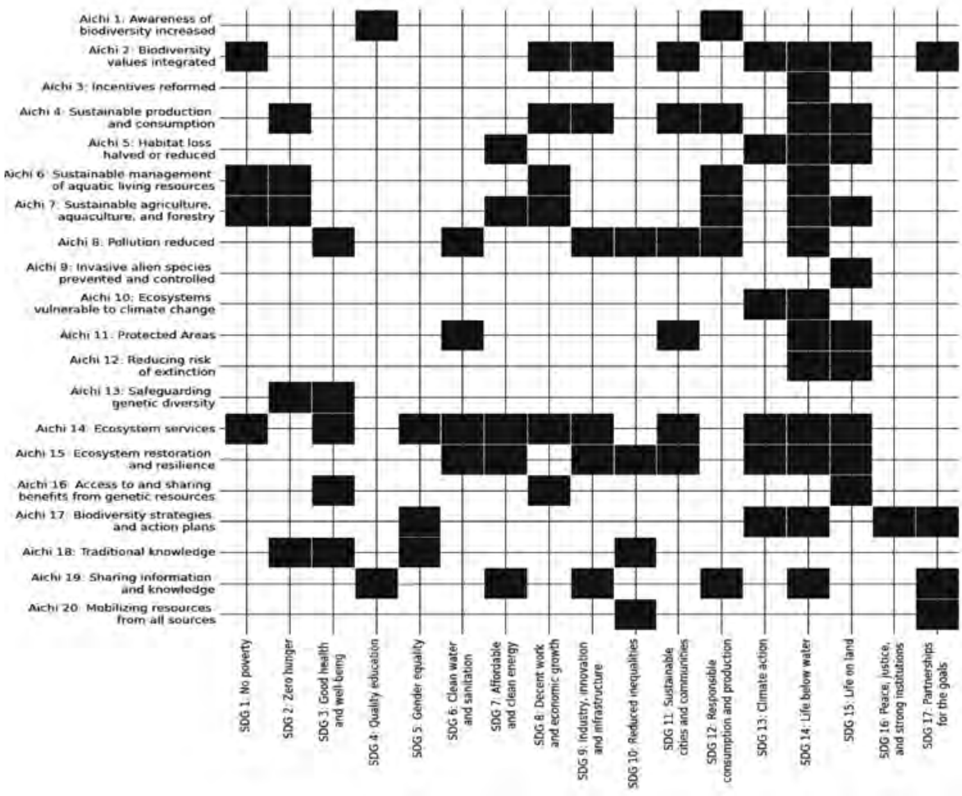
Table 1: Models of Assessment Indicators (Contd.

Category	*Focus*	*Number of Indicators*
Summary indicators		
Genuine Progress Indicator (GPI) [20]	Holistic monetised outcome (social, economic, environment)	1
Modified Gross National Income (GNI) [20]	Economic measurement	1
Ecological Footprint and Biocapacity Accounts (EFBA) [21]	Sustainability	1
Subjective Well-being (SWB) [22]	Well-being	1
Climate Change Adaptation Scorecard (CCAC) [23]	Climate change adaptation	1

Source: Authors' analysis based on: 1 (Byrne and O'Rourke, 2023), 2 (United Nations, 2023; 2024), 3 (United Nations Development Programme, 2024), 4 (European Commission, 2024), 5 (Central Statistics Office, 2023a), 6 (Maes *et al*., 2020), 7 (Secretariat of the Convention on Biological Diversity, 2016b), 8 (National Parks and Wildlife Service, 2024), 9 (IPBES, 2019), 10 (Environmental Protection Agency, 2023a), 11 (United Nations Department of Economic and Social Affairs, 2015), 12 (South Pacific Applied Geoscience Commission (SOPAC), 2004), 13 (Disaster Risk Management Knowledge Centre (DRMKC), 2024), 14 (Block *et al.,* 2024), 15 (Schwab and Zahidi, 2020), 16 (Institute for Economics and Peace, 2024), 17 (Institute for Economics and Peace, 2023), 18 (Richardson *et al.,* 2023), 19 (Kubiszewski *et al.,* 2013), 20 (Timoney, 2023), 21 (Dworatzek *et al.,* 2024), 22 (Diener 1984; Diener *et al.*, 2015), 23 (Climate Change Advisory Council, 2024).

The CBD Aichi Biodiversity Targets included 162 indicators organised under five strategic goals (Secretariat of the Convention on Biological Diversity, 2016b). These have recently been condensed and simplified into 23 targets in the Kunming-Montreal Framework. Figure 1 highlights their substantial overlap. In particular, Aichi Target 14 on ecosystem services correspond to SDGs 14 and 15. Ireland's fourth National Biodiversity Action Plan (NBAP) for 2023-2030 (National Parks and Wildlife Service, 2024) mostly tracks the establishment of supporting frameworks for biodiversity preservation. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) provides 71 indicators divided into areas such as biodiversity change drivers, ecosystem functions, and human well-being (IPBES, 2019). These provide additional votes, within our methodology, on which of the substantial number of indicators available from the CBD-Aichi Targets should be focused.

Figure 1: Correspondence Between SDGs and Aichi Biodiversity Targets



Source: Authors' illustration based on Secretariat of the Convention on Biological Diversity (2016a).

Climate change indicators are generally categorised into mitigation and adaptation monitoring, where the former receives substantial attention across datasets in terms of greenhouse gas monitoring. Adaptation, instead, is harder to quantify as it tends to be location-specific and focused on threat reduction (Barnett *et al.*, 2008). The Intergovernmental Panel on Climate Change (IPCC) provides general recommendations (Intergovernmental Panel on Climate *et al.,* 2023). Still, implementation and monitoring is through national requirements such as Ireland's Climate Change Assessment (ICCA) Climate Action Plan (Environmental Protection Agency, 2023a). The Sendai Framework for Disaster Risk Reduction (SFDRR) further explores risk reduction and resilience monitoring through four priority areas: understanding disaster risk, strengthening risk governance, investing in risk reduction, and enhancing disaster preparedness (United Nations Department of Economic and Social Affairs, 2015).

Other indicators assessing vulnerabilities and resilience around global climate change are evident from the Environmental Vulnerability Index (EVI) (South Pacific Applied Geoscience Commission (SOPAC), 2004), the Economic and Environmental Vulnerability Index (another EVI) (Guillaumont *et al.,* 2021), and the United Nation's Multidimensional Vulnerability Index (UN-MVI). Vulnerability indicators, however, tend to be more invariant to domestic land use policy in the short term and dependent on climate conditions. Resilience indicators include some that can be supported through land use changes, such as ensuring the adequacy of cropland, tree cover, diversification of the economy and sufficient household incomes to support savings and asset accumulation. For broader vulnerability assessments, the INFORM Index for Risk Management evaluates risk levels due to crises likely to overwhelm national responses (Disaster Risk Management Knowledge Centre (DRMKC), 2024).[1]

Several frameworks of indicators provide additional perspectives. The Environmental Performance Index (EPI) combines indicators across ecosystem vitality, environmental health, and climate mitigation (Block *et al.,* 2024); the Global Competitiveness Index (GCI) focuses on long-term economic growth and labour market conditions (Schwab and Zahidi, 2020) but environmental factors are minimal; the Global Peace Index (IEP-GPI) measures societal "peacefulness" related to conflict, violence, and social stability (Institute for Economics and Peace, 2024); and the Ecological Threat Report (ETR) complements the IEP-GPI by assessing environmental stressors, including risks of disaster displacement and food insecurity (Institute for Economics and Peace, 2023).

Summary indicators offer an alternative to indicator sets by distilling data into key measures that reflect the net effect of land use policy impacts. These indicators

[1] INFORM Climate Change – part of this framework – rates Ireland's risk as "very low" overall, though local-scale flood risk remains significant (Poljanšek et al., 2022). The national ranking does not, however, inform on whether some areas of Ireland would benefit from resilience building.

simplify reporting but may obscure details that would allow efficient diagnostics for policymakers. Nevertheless, they offer value as high-level metrics for assessing policy effectiveness, sustainability, and socio-economic progress. Summary indicators of interest, also reported in Table 1, focus on national output, environmental impacts, and adherence to planetary boundaries relevant to a country such as Ireland's ecological stability.

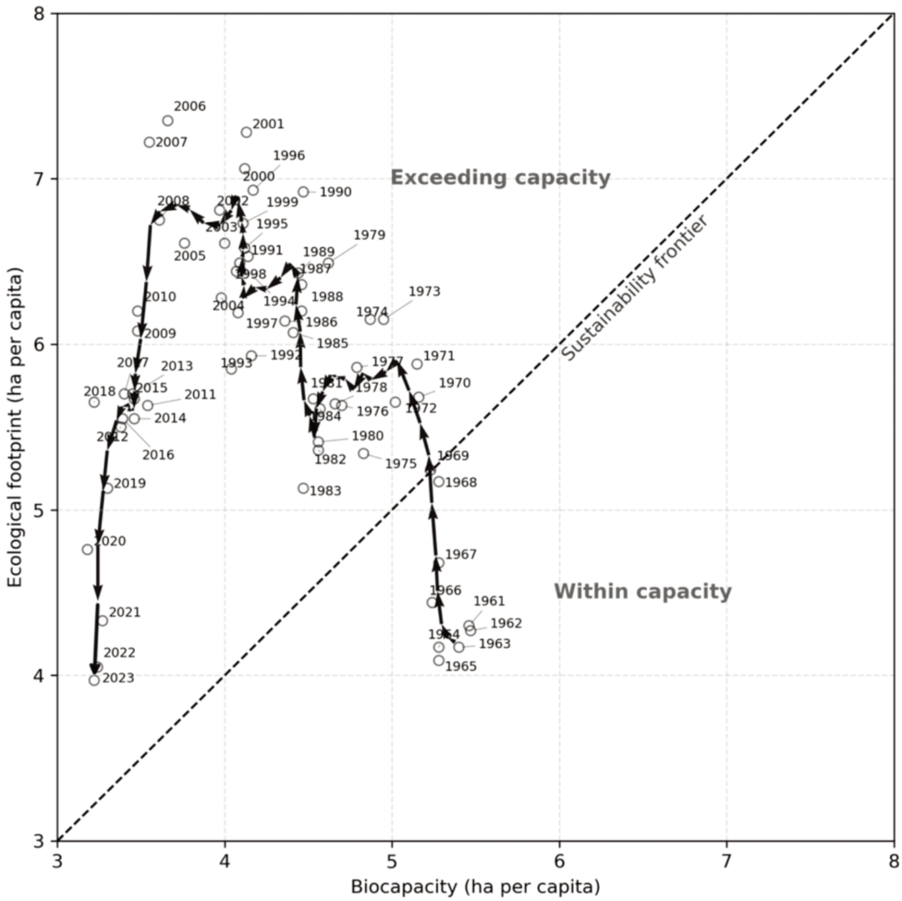
Particularly in the context of land use policy, summary measures of economic activity may overlook the long-term environmental and social impacts of land use, e.g. an expansion of agricultural production may boost GNI but lead to biodiversity loss and increased greenhouse gas emissions. Subsequently, measures such as the Genuine Progress Indicator (GPI) have been developed to adjust for non-market goods and services and the value of natural capital (Kubiszewski *et al.,* 2013).

The Ecological Footprint and Biocapacity Accounts (EFBA) could also provide a national measure of resource use versus biocapacity, i.e. the ability of the land to meet demand for renewable resources and ecosystem services (Dworatzek *et al.,* 2024). Overshoot occurs when demand exceeds biocapacity, signalling reliance on external resources or unsustainable consumption. In our case study to follow, we observe that Ireland has consistently exceeded capacity since 1969, as depicted in the phase diagram in Figure 2. Despite recent declines in the per capita footprint, overshoot continues due to the degraded nature of Ireland's resources. This is particularly alarming as the biosphere provides a foundation for economic activities (Dasgupta, 2021) and continued overshooting may eventually degrade all economic activity (Groom and Turk, 2021).

Subjective well-being (SWB) captures individual self-assessment of happiness and life satisfaction and serves as a complement to resource-based measures like the Ecological Footprint. Rooted in psychology (Diener, 1984), it has continued to develop as an alternative or complement to income measures (Diener *et al.*, 2015; Sen, 1995). It is already being implemented in some countries, for example, via the Well-Being Framework (Government of Ireland, 2024b) and Well-being Information Hub (Central Statistics Office, 2024i). Another alternative is the Capability Approach (Sen, 1999) which emphasises people's abilities to achieve valued outcomes but requires complex data and is more applicable to developing economies in focus.

The Stockholm Resilience Centre's (SRC) planetary boundaries outline nine critical thresholds for maintaining Earth's stability by limiting human impacts on key Earth systems (Richardson *et al.,* 2023). These boundaries cover diverse areas, including climate change, biosphere integrity, ocean acidification, and biogeochemical flows, highlighting limits beyond which rapid environmental change could disrupt our interconnected systems. Some boundaries are more relevant to Ireland than others, e.g. abundant rainfall minimises water scarcity risks, and ozone depletion is primarily addressed through international agreements (Environmental Protection Agency, 2021). However, climate drivers like CO_2

Figure 2: Ecological Footprint and Biocapacity Estimates, Republic of Ireland



Source: Authors' illustration based on data in Dworatzek *et al.* (2024).
Notes: Black arrows indicate direction of change based on 5-year rolling averages.

emissions and nutrient flows, which are heavily influenced by land use and production, directly impact Ireland's environment and are critical for guiding policy on sustainable practices.

Although the SRC's framework focuses on environmental thresholds, it lacks socio-economic dimensions, limiting its capacity to fully assess human welfare. Thus, combining socioeconomic, other environmental, and production metrics with such indicators could better fit our purposes. Additionally, some boundaries, such as genetic diversity, may be better assessed through proactive metrics like ecosystem productivity (net primary product) rather than reactive indicators like extinction rates. Remote sensing for atmospheric aerosols – though challenging due to Ireland's cloud cover – and tracking novel pollutants such as per- and polyfluoroalkyl substances (PFAS) represent important but complex monitoring requirements for effective risk management.

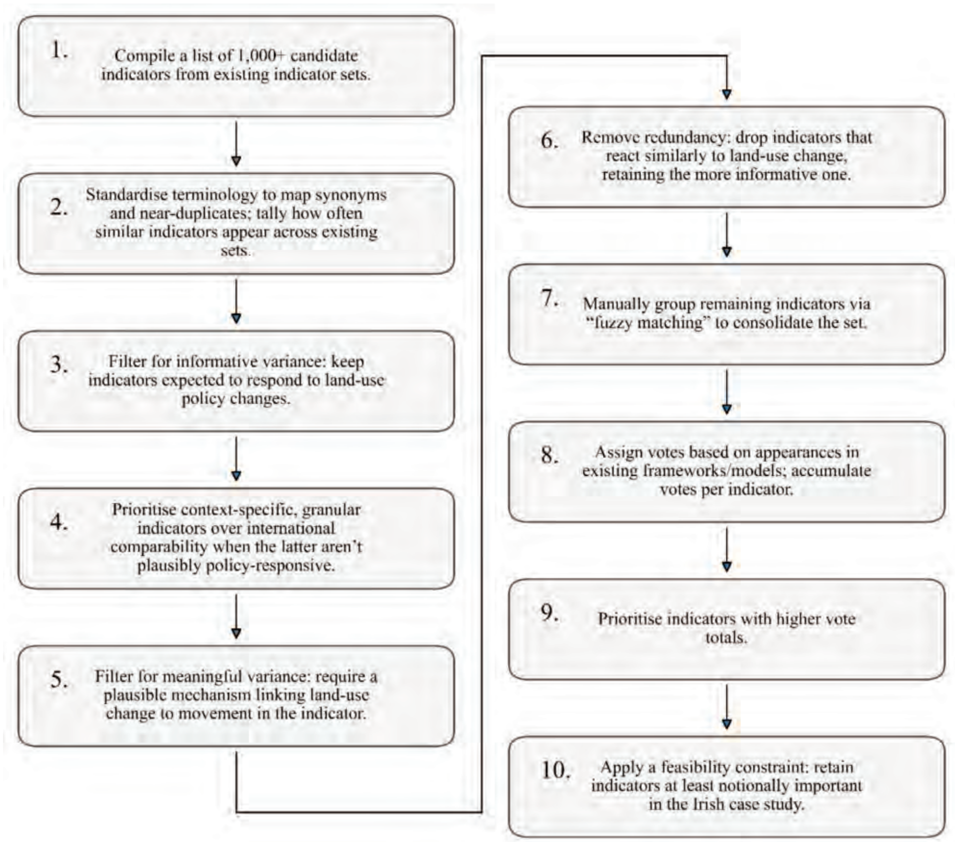
2.3 Indicator Selection

We find that comparing and combining indicators from different sources presents significant challenges. Indicator sets tend to differ substantially in terminology, scope and data requirements corresponding with diverse researcher perspectives and the disciplines they are drawn from. Even when indicators appear similar in scope and units of measurement, methodological divergences – for instance, in ecosystem service valuation techniques (Boyd and Banzhaf, 2007) – can hinder comparability (Baumgärtner *et al.,* 2015). Definitions may carry author-specific meanings, and consensus on indicator weighting remains elusive (Sachs *et al.*, 2024).

As depicted in Figure 3, we use a structured process to navigate indicator selection from over 1,000 identified candidates. First, we standardise the terminology of indicators where possible, enabling us to identify the frequency with which similar indicators are recommended in different indicator sets. Second, we focus on indicators likely to exhibit "informative variance" which we define as those expected to respond to land use policy changes. While internationally comparable metrics are valuable, particularly in demonstrating progress towards EU commitments, they are not always plausibly responsive to land use policy-driven changes at a granular scale. We instead prioritise indicators that change with conditions on the ground and enable effective, context-specific monitoring. We then narrow our focus further to indicators where we would expect to find "meaningful variance" – those where plausible mechanisms link land use changes to changes in specific indicators. We would not, for example, want to include two indicators which react similarly to land use changes as the additional indicator would add little value. We then further manually group indicators with similar meanings or functionality as a "fuzzy matching" approach. From this point, if an indicator appears in an existing framework or model, it receives a vote. Indicators accumulating more votes are prioritised for inclusion. Indicators are further constrained to those that are at least notionally measurable in our case study of the Irish context.

The resulting set of refined indicators span key domains. Socio-economic metrics from SDGs, GCI, IEP-GPI, and ETR track governance, infrastructure, urban sprawl, income, employment, poverty rates, financial stability of land-dependent firms, and GDP losses from disasters. Public engagement and well-being indicators capture attitudes toward land use, public engagement, and subjective well-being. Biodiversity and ecosystem health metrics emphasise species abundance, habitat quality, extinction risks, and invasive species, with a focus on birds and ecosystem resilience. Air quality and climate sustainability indicators monitor CO_2e emissions, air pollutants (ozone, sulphur dioxide, VOCs,

Figure 3: Indicator Selection Process



Source: Authors' illustration.

particulates), material footprints, carbon intensity, disaster preparedness, and climate adaptation. These may also be adjusted to account for statistical life values and mortality rates (Keller *et al.,* 2021). Water and soil health is assessed through nutrient pollution (ammonia, phosphates, nitrates), pesticide runoff, soil phosphorus, nitrogen retention, organic matter, and erosion rates. Production and resource use metrics include yield, biomass changes, profitability per acre, total production, carbon intensity of land use, ecosystem service values, and carbon storage capacity. Energy and infrastructure indicators cover energy demand, renewable fuel production, and sustainable transport infrastructure. Finally, summary metrics such as GNI, GPI, ecological footprint, and HDI provide an overarching assessment of production, societal, and environmental conditions.

We also note that ecosystem condition is a cross-cutting concept within this framework rather than a standalone category. In practice, ecosystem condition reflects the combined state of biodiversity, soil, water, and air, as well as their functional interactions, and is therefore captured through multiple domain-specific indicators rather than independent composite measures in our framework. This differs from ecosystem-type-based accounting approaches, such as those being developed under the Central Statistics Office's Ecosystem Accounts, which are designed to meet European Union reporting requirements by ecosystem type. Our objective is to structure indicators around how land use can be managed in practice, while still supporting ecosystem condition accounting through the reporting of relevant environmental statuses. As such, the proposed framework remains complementary to ecosystem accounting activities.

Notionally, tracking metrics such as government spending effectiveness, local strategy adoption, and EU programme outcomes for land use and conservation would also be valuable. However, as monitoring metrics become more granular and diverse, implementation challenges increase. Assessing environmental protection stringency and reducing harmful subsidies in agriculture and fisheries are priorities that remain difficult to quantify. We have also come to the conclusion that, for transparency, indices across multiple indicators should be avoided as they obscure data collection requirements and complicate interpretation, making it challenging to discern the contribution of individual components.[2] Additionally, aggregation often removes native units of measure, such as hectares of land use or tons of CO_2 for emissions, notionally complicating interpretation. With these caveats in mind, we have organised our selection of indicators into an integrated framework.

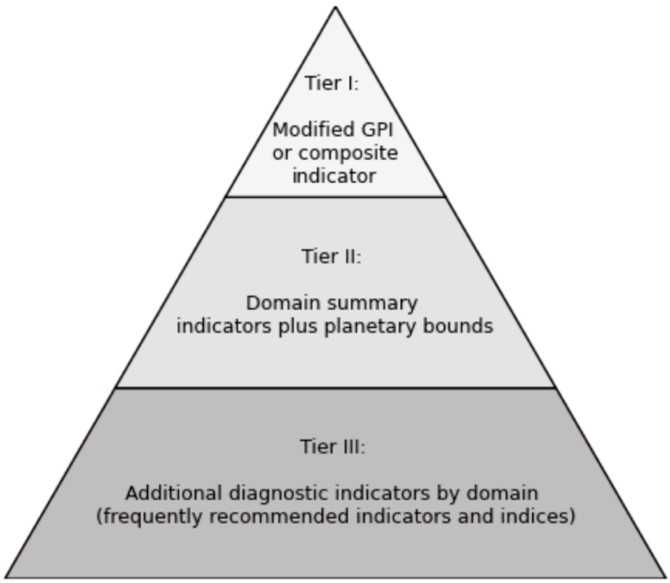
III AN INTEGRATED FRAMEWORK FOR LAND USE ASSESSMENT

We propose a multi-tiered assessment framework for evaluating land use policy impacts to address the broad scope of recommendations from previous indicator sets. A composite metric at the top level captures net changes across domains, providing an overall well-being measure. Tier II includes headline indicators for production, socio-economic and environmental outcomes, while Tier III consists of detailed diagnostic indicators to focus on when policy changes do not yield expected results. This framework is illustrated in Figure 4. Additionally, debate exists over whether growth-based indicators remain relevant if planetary boundaries are exceeded, as environmental limits ultimately constrain all other metrics. To reflect this, Ireland-specific planetary boundary contribution metrics are included

[2] This critique of composite indices does not apply to summary indicators like SWB, GNI, or GPI, which aggregate data in a common unit (e.g. euros) and concept. In contrast, composite indices merge heterogeneous metrics (e.g. land use, emissions, biodiversity) into a single score. While summary indicators have their own limitations, including an inherent loss of detail, they differ fundamentally from indices that merge disparate data into a single score.

in Tier II, with the possibility of elevating them to Tier I or above all other indicators if they become more clearly limiting.[3]

Figure 4: Assessment Framework Tiers



Source: Authors' illustration.

3.1 Tier I Composite Indicator

The Tier I indicator aims to offer a broad measure of progress toward sustainable development. One approach is a tailored Genuine Progress Indicator (GPI) that starts with an economic measure such as GNI and then accounts for environmental degradation and social externalities. GPIs are gaining traction as a comprehensive alternative to GDP, as they potentially provide a broader measure of economic welfare by accounting for factors like environmental degradation, social inequality, and non-market and public goods values (Barrington-Leigh and Escande, 2018). Unlike GDP, GPI adjusts for negative externalities such as pollution, resource depletion, and income inequality (Kubiszewski *et al.,* 2013; Berik, 2020). One construction of the GPI could be:

$$GPI = GNI^{*}_{\varepsilon} + NMP + NCC$$

[3] Trade-offs and synergies between indicators should also be assessed to ensure policy coherence. Evaluating trade-offs requires careful consideration when pursuing one objective might undermine another and, conversely, when synergies could be leveraged to maximise overall impact. These may need to be evaluated on a case-by-case basis.

where GNI^*_ε is Ireland's modified gross national income, which is inequality-adjusted (discussed in greater detail in the online supplementary material). *NMP* then represents the value of services provided from non-market and public goods, both natural and built. *NCC* is the change in the net value of natural and built capital, including adaptation and resilience expenditures and other investments. This process then involves monetising various environmental and social factors often omitted from conventional economic measures. For example, GPI subtracts the costs associated with pollution, carbon emissions (including adaptation and mitigation), biodiversity loss and resource depletion. It also adds in positive externalities like ecosystem services and social welfare. However, widespread adoption of GPI has been limited due to data requirements, particularly for non-market public goods and monetising environmental and social impacts.

An alternative to GPI is a composite index that summarises progress across socio-economic, environmental, and production dimensions using Tier II indicators. However, assigning weights to each indicator is inherently subjective (OECD, European Union, and Joint Research Centre - European Commission, 2008). Stakeholder disagreements, such as trade-offs between economic growth and environmental protection, could challenge the legitimacy and robustness of the index. Additionally, a composite index does not provide new information beyond what Tier II indicators already offer, serving only as a summary score. The choice between these approaches depends on feasibility. GPI is theoretically comprehensive but data-intensive, while the composite index is simpler but adds no new insights beyond Tier II indicators.

3.2 Tier II Domain Summary Indicators

Tier II indicators would supplement Tier I by providing relatively high-level summary metrics on socio-economic, production and environment domains separately, resilience to future challenges, and monitoring planetary bounds-related issues. While less detailed than follow-on Tier III indicators, these metrics serve as crucial intermediaries, synthesising broader trends to inform policy adjustments and guide diagnostic work. Along with the Tier I indicator, the suggested Tier II indicators are reported in Table 2.

Each domain indicator offers a broad measure of national well-being, resource use, or environmental sustainability. Subjective well-being (SWB) captures non-economic welfare, using survey-based measures to reflect quality of life, mental health, social cohesion, and personal satisfaction, aligning with SDG goals. In the production domain, per capita gross income or product serves as a key measure of wealth and spending potential, acting as a local equivalent to GNI. Ideally, this metric would be adjusted for inequality, such as equally distributed equivalent (EDE) income, to assess economic growth alongside equity. Including these indicators in Tier II ensures economic development remains linked to social and environmental sustainability.

An ecological footprint relative to biocapacity would gauge whether resource use aligns with the environment's regenerative capacity, directly addressing sustainable consumption goals. This indicator reveals if resource consumption and waste generation exceed environmental carrying capacity, signalling potential overshoot. The complexity of adapting to climate change presents significant methodological challenges, and building resilience is increasingly vital. A survey-based climate adaptation index, expanding on Ireland's Climate Change Adaptation Scorecard, could assess local climate risk readiness. This measure would gather data from local governments on infrastructure resilience, policy frameworks and adaptive capacity to evaluate preparedness for climate disruptions and extreme weather.

Planetary Boundary indicators, such as CO_2e emissions, biosphere integrity, and chemical releases are key for tracking sustainable development. Genetic diversity can be assessed using the IUCN Red List or Living Planet Index. At the same time, Net Primary Production (NPP) provides insight into ecosystem resilience and biomass generation, preferred over the Biodiversity Intactness Index (BII). While forest cover is emphasised in the Planetary Boundaries framework, a broader land cover approach supports balanced land management. Chemical flows, particularly nitrogen and phosphorus in surface and groundwater, are critical for assessing nutrient loading from agriculture and urban waste, which can drive eutrophication and threaten water quality. These indicators are also essential for CAP assessments and align with SDGs and Aichi Targets. Monitoring novel entities, such as PFAS, is increasingly vital due to their persistence, bioaccumulation, and health risks. While air quality has improved in many areas, aerosol optical depth remains relevant for tracking particulate concentrations in colder months.

Following the identification of issues via Tier II outcomes, it would then be prudent to examine supporting data or conduct further research. Therefore, we recommend Tier II indicators be backed by specific diagnostic indicators at the Tier III level to allow for deeper analysis and targeted action.

3.3 Tier III Diagnostic Indicators

Proposed Tier III indicators provide in-depth diagnostics relevant to land use changes, structured into sub-domains related to environmental, production, and socio-economic outcomes. Due to the broad impacts of land use on the environment, metrics are further divided into air quality, biodiversity, climate change, production, socio-economic, soil and water categories, as reported in Table 3. While ecosystem condition is not represented by a single indicator, Tier II and Tier III indicators collectively capture changes in ecosystem condition through measures of biodiversity status, water and soil quality, air pollution and functional integrity.

Air quality is closely linked to land use, particularly in agriculture, where ammonia (NH_3) from fertilisers and methane (CH_4) from livestock are key pollutants. NH_3 affects respiratory health, while CH_4 contributes to climate change and ozone formation, impacting health and crop productivity. Tracking these pollutants informs agricultural management. An Air Quality Index (AQI) aggregates pollutants (e.g. $PM_{2.5}$, NO_2) to assess cumulative impacts. Waste and water quality indicators capture ecosystem effects of land use. Municipal solid waste reflects consumption trends, recycling rates track circular economy progress, and wastewater treatment protects waterways. A Water Quality Index (WQI) could complement Water Framework Directive monitoring (Environmental Protection Agency, 2021) by tracking secondary pollutants like pH, dissolved oxygen, and E. coli. Biodiversity indicators could assess ecosystem health through species richness, the macroinvertebrate index for aquatic health, IUCN Red List data on extinction risks, and the Biodiversity Habitat Index (BHI) for habitat quality.

Land use also influences socio-economic metrics, including household income, employment, and service access. While Tier II includes household income, rising living costs underscore the importance of income net of expenses as a metric. Employment in land-intensive sectors such as agriculture highlights land's economic role, while infrastructure access – especially net-zero infrastructure – reflects urbanisation trends impacting well-being. These indicators support sustaining agricultural and forestry practices. Additionally, separating farm household income from general household income provides insights into the unique economic challenges and opportunities in agriculture, making it a valuable stand-alone indicator.

Production indicators capture financial drivers of land use, incorporating both market and non-market values. Key measures include agricultural yields, forestry for timber and carbon sequestration, and urban, industrial, and natural land productivity. Monitoring urban and industrial land productivity helps assess sustainable growth and economic output in resource-intensive sectors. Ecosystem services from wetlands, grasslands and recreational lands – such as water filtration, carbon storage, and public health benefits – are also critical. Soil health underpins productivity and environmental quality, supporting water regulation, nutrient cycling, and carbon sequestration. Soil organic matter (SOM) reflects soil fertility, while erosion rates indicate soil loss and sedimentation. A soil quality index could aggregate secondary metrics like nutrient balance and soil acidity for comprehensive monitoring.

Finally, climate change affects land use stability, with emissions tracking and adaptation readiness as key focus areas. Carbon intensity per hectare links emissions to agricultural and forestry practices. While Tier II assesses government adaptation efforts, public surveys provide additional insights into preparedness for climate events like floods and droughts. Monitoring progress on Climate Adaptation Action Plans (CAAPs) supports resilience and net-zero goals.

Tier III diagnostic indicators complement Tier I and II by supporting corrective actions related to land use policies. They are essential tools for policymakers seeking to refine and adapt land use strategies in response to changing production, environmental, and socio-economic conditions. They are intended to report changes in production status (food, fibre, and fuel), environmental, and socio-economic outcomes in response to land use changes. Therefore, they are also valuable for diagnosing which aspects are hindering progress or regressing. This can help policymakers decide what changes are needed to improve land use performance.

In summary, the Tier I recommendation, a modified Genuine Progress Indicator, summarises environmental, production, and socio-economic outcomes. Tier II indicators instead summarise the status of each of those three domains separately, supplemented by planetary boundary indicators (see Table 2). Finally, Tier III indicators have been carefully selected from among expert recommendations for diagnostic purposes to help policymakers identify aspects of the environment, socio-economic setting, and production outcomes which are falling short of targets or expectations (Table 3). Importantly, each tier ideally does not aggregate information from other tiers but is independently sourced. This aspect would help avoid entirely missing yet unidentified issues but also aids in validation by allowing for cross-referencing and comparison between tiers. For example, if a Tier II indicator suggests a lack of progress but all relevant Tier III indicators appear on target, an unknown factor or synergy between existing ones requires further exploration.

While each indicator has the native standard units that it is typically measured in, progress in each indicator might also be converted to a comparable scale by stating each in terms of their growth rates over the same period. Another option is to state each indicator in terms of underperformance or rate of divergence from a target (or expected) path. More importantly, developing time series data on each indicator is necessary to use the assessment framework proactively and repeatedly. We would also need that data to be sufficiently granular to be meaningfully linked to Land Use, Land-use Change and Forestry (LULUCF) changes.

3.4 Indicator Summary and the Irish Case Study

Proposing 36 indicators as set out in the preceding section for monitoring land use outcomes is the first step in a functional assessment framework. In any application, data sources must be identified, and an expansion of data collection will likely be required in most cases. To test the feasibility of the recommended framework, we assess the current availability of data in a specific case (Ireland). In the following tables in this section, we summarise not just our set of indicators, but also our findings on their data availability in Ireland. We classify each indicator by the domain it represents, and then we identify the current level and frequency of collection, organisations involved in their collection, and barriers to implementation or expanded collection.

The inadequacy of data collection is a well-documented issue in Ireland, leading to the commissioning of Ireland's *Land Use Evidence Review* (O'Rourke *et al.*, 2023). This section summarises data availability and collection limitations in the Republic of Ireland. We explore whether the relevant data are being collected, at what scale and frequency, and by which agencies, departments, or other interested parties. We generally find a disconnect between current data availability and information from unrelated sources. We discuss this in relation to the three tiers of our proposed integrated framework.

IV DISCUSSION

Our integrated assessment framework focuses on selecting insightful indicators to capture the impacts of land use across production, socio-economic, and environmental domains. These indicators provide a comprehensive overview while also pinpointing specific issues. The framework serves as a "shopping list" of data requirements, unrestrained by current data availability. However, challenges such as data accessibility and collection costs remain significant. Advances in technology, such as sensors, data analytics and artificial intelligence, can enhance the feasibility and affordability of data collection. Many proposed indicators also align with existing collection efforts, creating opportunities for collaboration to meet stakeholder needs efficiently.

Many indicators were reviewed but excluded to maintain a minimal yet sufficient selection that balances insight, practicality and cost. The chosen indicators estimate conditions effectively without imposing unnecessary financial burdens. Some, such as the Living Planet Index, Aerosol Optical Depth, and some marine-related metrics were also excluded despite their importance, as they lacked a strong connection to land use or offered limited returns on research investment. In developing our assessment framework, we also evaluated the adequacy of current land use and land cover data collection. CORINE is the most promising source within the European Union. However, its six-year reporting intervals limit its usefulness for timely decision-making compared to annual or quarterly updates in other sectors. However, with the end of CORINE land cover collection approaching, its replacement, CLCPlus, should provide both improvements in frequency – to a three-year interval – and resolution (European Environment Agency, 2024). While remote sensing has potential, its current capabilities do not fully meet this policy's needs. Further details on the indicators excluded and concerns regarding collection are discussed in the online supplementary material.

Our case study reveals that some relevant data for the suggested indicators are already collected in Ireland. Key sources include the CSO, EPA, and contributions from the NBDC, BirdWatch Ireland, Teagasc, Geological Survey Ireland, and the CCAC. However, fragmented data sources with differing mandates and capacities also create obstacles. The absence of a harmonised database of highly granular data hinders decision-making, progress monitoring and policy evaluation, highlighting the importance of developing a shared, streamlined data system.

Table 2: Suggested Tier I and II Indicators

	Indicator	*Standard units*	*Scale*	*Frequency*	*Agency/Entity*	*Barriers*
Overall	Modified Genuine Progress Indicator [1]	€ equivalent/ capita	–	–	Some components available from CSO, EPA, and NPWS	Lack of legal mandate
Domain summary	Subjective well-being (socioeconomic) [2]	score (0-10)	National	Annual	CSO	Insufficient sample size – risks re-identification
	Gross income or gross product per capita – GNI, GNP equivalents (production) [3]	€/capita	Regional	Annual	CSO	Insufficient sample size – risks re-identification
	Ecological footprint relative to biocapacity (environment) [4]	hectares/ capita	National	Annual	Ecological Footprint Initiative and the Global Footprint Network	No domestic capacity – relies on global datasets and coarse assumptions
	Climate change adaptation scorecard-based index (resilience and adaptation) [5]	score (0-12)- adjustable	National	Annual	CCAC	Further development of survey methodology
Planetary boundaries	CO_2e emissions (Climate change and ocean acidification) [6]	tonnes/year	National	Quarterly (formerly annually)	EPA	Increased emissions modelling capacity
	IUCN Red List as replacement for extinction rate) (Biosphere: genetic diversity) [7]	Index (0-1) on species survival	Dis-aggregated	6 years or more frequently	NPWS, NBDC and BirdWatch Ireland (partially citizen science-based)	Limited talent pool of ecological consultants to support measurement

Table 2: Suggested Tier I and II Indicators (Contd.)

	Indicator units	*Standard*	*Scale*	*Frequency*	*Agency/Entity*	*Barriers*
Planetary boundaries	Net primary product (NPP) or Biodiversity Habitat Index (BHI) (Biosphere: functional integrity) [8]	Carbon g/m^2 or intactness (0-100%)	–	–	Some supporting methodologies in development by Teagasc and EPA	Insufficient domestic capacity – relies on global datasets with coarse assumptions
	Surface and groundwater NO_3 and/or P concentrations (Biogeochemical flows) [9]	(mg/L)	Site-based	Varied, often 1+ times/year	EPA	Additional research on attribution to sources
	Land cover shares relative to target (expanded from forested land) (Land system change) [10]	hectares/ total	–	–	Coverage known, but targets require coordination between several groups	Multistakeholder agreement on land cover targets
	PFAS levels in surface and ground-water, particularly drinking water (Novel entities) [11]	ng/L	Site-based	Varied surface, 6-year interval groundwater	EPA is increasing monitoring since 2020, plus some prior one-off studies	Transparency on PFAS records and increased frequency of monitoring

Source: Authors' analysis based on: 1 (Stout *et al.,* 2023; Ní Dhúill and Sheehy, 2024; Parker *et al.,* 2016; Norton *et al.,* 2016; Central Statistics Office, 2024e), 2 (Wall, 2013; O'Brien, 2018; Central Statistics Office, 2024h; 2024g; Department of the Taoiseach, 2023), 3 (Central Statistics Office, 2024g), 4 (Dworatzek *et al.,* 2024), 5 (Climate Change Advisory Council, 2024), 6 (Nielsen *et al.,* 2020; Environmental Protection Agency, 2024d; 2024g; 2024i; 2024h), 7 (National Parks and Wildlife Service, 2020; National Biodiversity Data Centre, 2024), 8 (Saunders *et al.,* 2022; Fenton *et al.,* 2024; Teagasc, Environmental Protection Agency, and Cranfield University, n.d.), 9 (Hannigan and Kelly-Quinn, 2016; Environmental Protection Agency, 2024b), 10 (Lydon *et al.,* 2023), 11 (Uisce Éireann, 2016; Environmental Protection Agency, 2022; 2023b; n.d.). The online supplementary material provides a detailed assessment of data availability does not include indicators from the SRC that are not pressing in Ireland. Land cover shares would follow EU summary classifications.

Table 3: Suggested Tier III Indicators

	Indicator	*Standard units*	*Scale*	*Frequency*	*Agency/Entity*	*Barriers*
Air	Air NH_3 (Ammonia)[1]	mg/m^3	National	Annual	EPA and Teagasc	Increased production modelling capacities
	Air CH_4 (Methane)[2]	ppm	National	Annual (quarterly as part of CO_2e)	EPA and Teagasc	Increased production modelling capacity
	Air Quality Index (AQI)[3]	Index (0-500)	115 sites	Continuous	EPA	Additional research on attribution to sources
Biodiversity	Species richness [4]	Number of species	Sightings	Continuous	NBDC via citizen science continuous entries	Development of statistical methods to address selection bias
	Macroinvertebrate index on rivers [5]	Bio score	–	–	Not currently collected	Considerable collection on multiple species to measure biodiversity
	IUCN Red List status – disaggregated [6]	Threatened species count	Mixed	6 years or more frequently	NPWS (habitat or species-based infrequent reports) and NBDC (citizen science-based species reporting)	Limited talent pool of ecological consultants to support measurement
	Biodiversity Intactness Index (BII) [7]	Index (0-100)	–	–	One-time global estimates (not domestically produced)	No domestic capacity nor repeated global estimates

Table 3: Suggested Tier III Indicators (Contd.)

	Indicator	*Standard units*	*Scale*	*Frequency*	*Agency/Entity*	*Barriers*
Climate change	Carbon intensity of land use[8]	CO_2e tonnes/ hectare/year	National	Quarterly	EPA	Increased emissions modelling capacity
	Climate Adaptation Action Plan implementation[9]	% of planned actions implemented	Local govern- ment)	Annual (not yet available	Department of the Environment, Climate and Communications	Expansion of work that is in development
	Government preparedness for climate change (survey-based)[10]	Index	–	–	Could be appended to existing CSO survey efforts	Requires methodological development and perhaps a reporting requirement
Production	Agricultural yield (per hectare)[11]	kg/ha	Farm level	Annually	Teagasc	Insufficient sample size – risks re-identification
	Timber production (forestry)[12]	m^3/year	National	Annually	Department of Agriculture, Food and the Marine	Insufficient sample size – risks re-identification
	Urban employment as a proxy for urban land productivity[13]	Jobs created	Household	Quarterly	CSO	Insufficient sample size – risks re-identification
	Industrial land productivity[14]	€/m^2	Household	Quarterly	CSO	Requires methodological development
	Wetland ecosystem services[15]	€ or environmental value	–	–	Extent of wetlands measured; ecosystem services mostly unquantified	Requires substantial upscaling of research capacity

Table 3: Suggested Tier III Indicators (Contd.)

	Indicator	*Standard units*	*Scale*	*Frequency*	*Agency/Entity*	*Barriers*
Production	Grassland productivity[16]	kg/ha	Farms	Ongoing	Teagasc	Confidential data which would risk re-identification
	Recreational land use (parks, conservation areas)[17]	€ or visits per year	Individual	Ongoing	Fáilte Ireland, Coillte and CSO	Expansion of collection to more locations
Socio-economic	Discretionary income[18]	€, €/household	Household	Annually	CSO	Held as confidential, possibly sufficient
	Employment in agriculture, forestry, and other sectors[19]	% of population	Household	Quarterly	CSO	Insufficient sample size – risks re-identification
	Access to services and infrastructure[20]	% of population with access	Household	5 years	CSO and National Trasport Authority	Infrequent and limited in current collection scope
Soil	Soil health (organic matter levels)[21]	% Organic content	National requirement, detailed mapping	Not yet – 3-year interval starting in 2026	Preliminary mapping is underway. CSO EAD reporting to start in 2026	Requires repeated mapping and an update mechanism
	Soil erosion rate[22]	Tonnes/hectare/year	Site-based (~2,000)	Varied-1+ times/year	Some modelling completed. EPA measures indirectly as disaggregated estimates in water quality	Additional research on attribution to sources

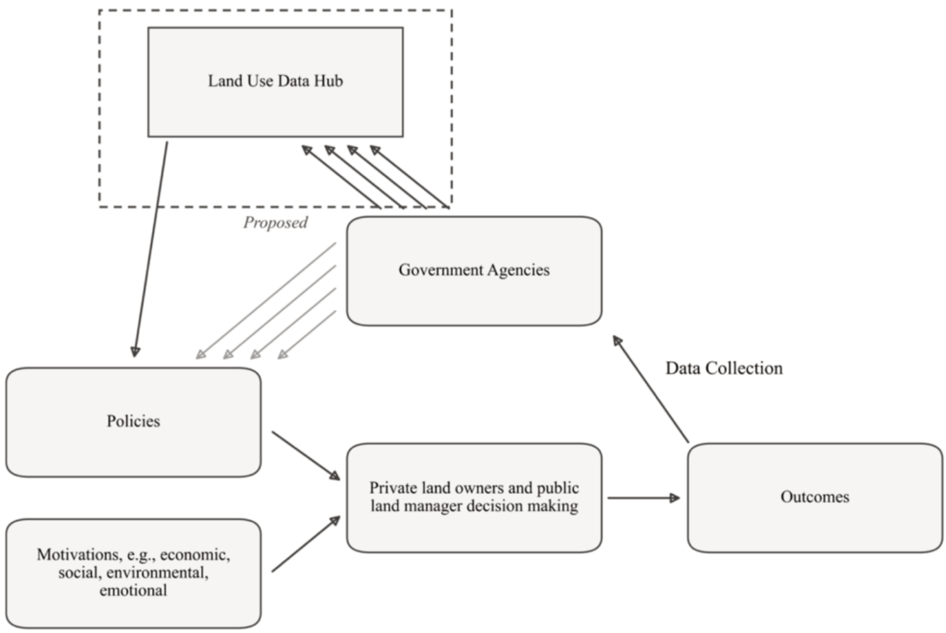
Table 3: Suggested Tier III Indicators (Contd.)

	Indicator	*Standard units*	*Scale*	*Frequency*	*Agency/Entity*	*Barriers*
Water	Wastewater treatment efficiency[23]	% Treated	Discharge point-based	Annual (licensing)	EPA	Likely sufficient
	Water Quality Index (WQI)[24]	Index (0-100)	Site-based (~2,000)	Varied-1+ times/year	EPA	Additional research on attribution to sources
	Ecological status	Bio-score	Site-based	Varied, often 1 + times/year	EPA	Additional research on attribution to sources

Source: Authors' analysis based on: 1 (Nielsen *et al.,* 2020; Owusu-Twum *et al.,* 2024), 2 (O'Brien and Shalloo, 2019; Nielsen *et al.,* 2020; Environmental Protection Agency, 2024d; 2024f; 2024h), 3 (Environmental Protection Agency, 2024a), 4 (National Biodiversity Data Centre, 2024; National Parks and Wildlife Service, n.d.), 5 (Environmental Protection Agency, 2020; 2024l; Inland Fisheries Ireland, 2024b; 2024a), 6 (National Parks and Wildlife Service, 2020), 7 (Hudson *et al.,* 2014; Phillips *et al.,* 2021), 8 (Environmental Protection Agency, 2024e; 2024j; 2024g), 9 As expansion of Climate Change Advisory Council (2024), 10 No current capacity, but could conceptually be attached to existing CSO collections such as Central Statistics Office (2024h), 11 (Teagasc, 2024a; 2024b), 12 (Department of Agriculture, Food and the Marine, 2024; Central Statistics Office, 2023b).13 (Central Statistics Office, 2020), 14 (Central Statistics Office, 2020; 2024f; O'Driscoll *et al.,* 2023), 15 (Wetland Surveys Ireland, 2024), 16 (Teagasc, 2021), 17 (Department of Rural and Community Development, 2022; Coillte, 2021), 18 (Central Statistics Office, 2024b; 2024d), 19 (Central Statistics Office, 2024f), 20 (Central Statistics Office, 2019a; 2019b; 2024a; National Transport Authority, 2024), 21 (Geological Survey Ireland, 2024a; 2024b; Geological Survey Ireland and Teagasc, 2024), 22 (Environmental Protection Agency, 2024l; Kiely *et al.,* 2014; Eurostat, 2020; Joint Research Centre - European Soil Data Centre, 2024), 23 (Environmental Protection Agency, 2017; 2024k), 24 (Environmental Protection Agency, 2024c). The online supplementary material provides a detailed assessment of data availability.

It is perhaps helpful to consider where, in the flow of responsibilities and information, an integrated land use data hub would fit as outlined in Figure 5. Government agencies play a key role in land management, and they are also to the fore of data collection on the outcomes of land use. This includes the addition of a proposal for a centralised land use data repository. The repository would ensure that policymakers have the most relevant data available rather than relying on heterogeneous experience regarding which agencies and individuals to contact. The inclusion of a data repository would not preclude other channels of communication but rather would inform on some of the information possibilities.

Figure 5: The Policy and Data Collection Landscape in Ireland



Source: Authors' illustration.

We have also found that national agencies frequently report estimates on critical topics, but providing greater detail in the sources of underlying information and methodologies would benefit end users. At a minimum, statistics should include links to sufficient data to enable replication of analyses, aligning with modern research standards for transparency and replicability. However, we find that agencies do not always provide adequate contact information for data creators, instead providing generic points of contact. Greater integration of methodologies with reported data would significantly enhance usability and reliability. We also recommend the development of a national land use monitoring authority. This would be a dedicated agency or interdepartmental body that would coordinate land use and outcome data collection and collation. Ideally, all data would be available from one land use data hub.

In many cases, relevant data are collected but reported only at the national scale, likely due to concerns over small sample sizes. This limits their usefulness for linking land use policy changes to local decision-making. The challenge often lies not in data collection but in the lack of detailed dissemination. However, when increasing data granularity, precautions must ensure individual identities remain protected in compliance with the General Data Protection Regulation (GDPR). In other cases, particularly on environmental reporting, substantial one-off collection efforts have been undertaken, sometimes at highly granular scales. While incredibly valuable, integrating such research into an assessment model requires transitioning to a recurring collection framework. This shift would benefit from institutional changes that prioritise long-term data collection over isolated studies.

In addition, significant knowledge gaps remain. For example, collection of PFAS or POP levels in Irish waters and soils, particularly those transported via biosolids in agriculture, is underdeveloped and not publicly reported beyond a one-off national metric. This represents a critical gap requiring an entirely new research agenda. EFBA, NPP, and BHI indicators should also be derived from disaggregated, Ireland-specific estimates rather than global remote-sensing metrics. This will require extensive fieldwork and a framework to update estimates following land use changes and the progression of global climate change.

Expanding small-scale efforts, such as the CCAC's scorecard framework, is essential for developing efficient, quantitative assessments. A complementary approach could integrate public perceptions of preparedness into existing surveys. Similarly, the European Union's nascent natural capital accounting initiative shows promise but requires additional investment to establish standards and a monitoring framework. Another challenge is the natural scale of data, which often mismatches land use assessment needs. For example, water data are organised by catchments, complicating integration with other datasets. Pollutant attribution is further hindered by movement through air and water. Addressing these issues requires a harmonised data system and methodologies for better usability and comparability. Additionally, land use changes often lag policy cycles, necessitating tempered expectations to match physiological limitations.

Finally, we note that data collection in Ireland is often driven by satisfying legal requirements. Collection is then organised following the enactment of legislation which is itself often a response to changes in European Union requirements. As such, substantial delays have occurred between changes in European Union or Irish legislation and data availability. It can also be that, as in the case of GPI, attempts have been made to pass legislation on an indicator's collection without success (Howlin, 2017; Nash, 2020). Preferably, a more streamlined process could be set up to move faster from concept to collection. Any such revised process would need to continue to place concerns about data ownership, security, and trust at the forefront as well as ensuring that GDPR standards continue to be upheld.

V CONCLUSION

This research reviews existing indicators and frameworks to assess the impacts of land use policy changes on environmental, socio-economic, and production outcomes. We propose a three-tier framework to balance our capacity to draw insights against the feasibility of implementation. The framework includes broad, integrative indicators, such as modified GPI, to detailed diagnostic metrics. While each indicator may present challenges regarding data availability and cost, collectively they could provide a practical, implementable means of capturing key land use impacts. Our case study in Ireland reveals that much of the data required to estimate these indicators are already being collected (as per Table 3), though often for different purposes or at inconsistent geographic scales. Significant revisions to existing efforts are necessary in some cases, often in relation to scale, frequency and sample size. For some indicators, no relevant data collection activity is currently in place.

Looking forward, ensuring cost-effective and adaptable monitoring approaches will be critical and this is why we propose a list of 36 priority indicators. As new data become available, advances in research on shadow prices and marginal benefits can be made, or as policy priorities shift, the framework should be refined, expanded, or revised to reflect these changes. Flexibility is particularly crucial given future uncertainties surrounding global climate change and its implications for land use.

In conclusion, selecting a minimally sufficient set of indicators that balances comprehensiveness with practicality is essential for effectively monitoring the impacts of land use change. This review is another step towards a comprehensive framework for assessing socio-economic, environmental, and production outcomes resulting from land use policy adjustments. The framework is intended to guide future efforts in creating a robust, adaptable monitoring system.

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