Online Supplementary Material to:
Measuring What Matters: An Integrated Framework for Assessing Land Use Outcomes

Details of indicator calculations

In this section, we provide additional details on indicator estimation. These are cases where additional details on collection might serve the interest of practitioners as guidance but are not necessary to our main recommendations.

Calculation of GPI

As noted in the main text, constructing the GPI would follow:

$$GPI = GNI_{\varepsilon}^{*} + NMP + NCC.$$

GNI_{ε}^{*} is Ireland's modified gross national income inequality-adjusted, *NMP* represents the value of services provided from non-market and public goods, both natural and built, and *NCC* is the change in the net value of natural and built capital inclusive of adaptation and resilience expenditures and other investments.

While there are alternative ways to adjust GNI to account for inequality concerns, the use of the Atkinson index has a strong theoretical basis (Atkinson 1970). It is also generally intuitive as an adjustment to reflect losses in societal welfare due to unequal income distribution – emphasising how inequality diminishes the benefits across much of society which should be received from economic output. The adjustment is based on multiplying Ireland's preferred measure of income, GNI^{*}, by the ratio of equally distributed equivalent income to mean income, $\frac{y_{\varepsilon}}{\bar{y}}$, the proportion of the mean income that society would consider equally valuable if all incomes were distributed equally, given society's level of inequality aversion. This is based on mean income, $\bar{y}$, and equally distributed equivalent income,

$$y_{\varepsilon} = \begin{cases} \frac{1}{N}\sum_{i=1}^{N}\frac{y_i^{1-\varepsilon}}{1-\varepsilon}, \varepsilon \neq 1, \varepsilon \geq 0 \\ \frac{1}{N}\sum_{i=1}^{N}\ln(y_i), \varepsilon = 1 \end{cases}$$

[1] Cork University Business School, University College Cork

[1] Teagasc (Agriculture and Food Development Authority)

* Corresponding author: ZTurk@UCC.ie

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based on household incomes, y_i, and societal elasticity of marginal utility of consumption, ε. Nationally, this is generally close to but above one in Ireland, e.g., 1.00 or 1.47, depending on the point of reference in Evans' marginal versus average tax-based approach (Evans 2005), and 1.08 based on the rate of inequality growth in (Turk 2024). A value close to one means income distribution does not significantly diminish perceived societal welfare.

Traditional income, GNI-equivalent indicators, e.g., household-scale earnings, are collected across Ireland (Central Statistics Office 2023a). These would then be adjusted for transfer payments to households. To conduct an inequality adjustment along the lines of (Atkinson 1970) and (Sen 1976), however, would require a similarly granular measure of the elasticity of marginal utility of consumption, η, which has yet to occur. Yet, it is entirely reasonable that η could differ across Ireland rather than using national average estimates from (Evans 2005) or (Turk 2024), and the latter offers a method to estimate η at disaggregated levels.

Non-market and public goods, *such as NMP,* partly capture society's 'hidden scaffolding'. These are a wide variety of untraded goods and services on which the economy and society depend. In socio-economic terms, this includes the values of unpaid household labour and community volunteer work and the direct and indirect value received from living in a well-functioning society. NMP is also net of costs resulting from a developed society, such as the cost of crime and unemployment, and more mundane issues, such as lost value from commuting times. NMP also includes other public service flows, e.g., from public health and education. Regarding the environment, NMP potentially includes an expansive number of sources of ecosystem services, which are subsequently reduced in response to destructive activities. These include but are not limited to regulating services over air, climate, disease and pests, pollination, erosion, water flow rates, water purification, and water treatment.[1] Environmental detractors from NMP include any additional losses in value not attributed to differences in the value of ecosystem services including losses in existence values due to environmental degradation – in part an environmental parallel to the value received from a well-functioning society.

Net Capital Change, NCC, includes changes in the value of both natural and built capital rather than flows. This includes the value of renewable and non-renewable natural resources (mineral deposits, tree stands, stocks of species, soils, climate), built capital – both private and public – and potentially human capital as a less physical form of built

[1] For a list of examples studies of regulating and cultural services from the environment see Table 2 in (Drupp et al. 2024).

capital.[2] Subsequently, the overconsumption of renewable forms of NCC today reduces the value we might receive from them in the future, as does the inefficient transformation of non-renewable NCC into built capital. We also note that NCC changes in terms of natural capital, may involve changes in the value of long-lived – even perpetual – resources and so will be sensitive to the application of appropriate social discounting methods. Current national recommendations in Ireland include the Ramsey rule-based social rate of time preference (SRTP) approach (Ramsey 1928; O'Callaghan and Prior 2018; Department of Public Expenditure and Reform 2019).[3] This basis has the social discount rate determined as:

$$SDR = \mu + \eta\bar{g}$$

based on the pure rate of time preference, μ, elasticity of marginal utility of consumption, η, and mean growth rate in consumption per capita, $\bar{g}$.[4] Societal long-run perspectives on the future, inequality, and growth potential may differ across Ireland, resulting in different estimated values on NCC, even for similarly long-lived resources. NCC will also be sensitive to whether we value natural capital at market rates or on an explicitly environment basis (Weikard and Zhu 2005; Hoel and Sterner 2007) which can substantially change – generally uplifting – the value of natural capital (Baumgärtner et al. 2015; Drupp et al. 2024).

Calculation of NPP and HANPP

Estimation methods for NPP and HANPP follow distinct paths. HANPP can be arrived at by carefully accounting for land use, e.g., monitoring the productivity of agriculture, including livestock, silviculture, and other land uses. NPP is then modelled using assumptions on how observed outputs and often changes in land cover relate to carbon retention in the environment. Through land use and population densities, carbon retention and extraction via human appropriation are then used to map HANPP and NPP estimates, sometimes at a global scale, e.g., (Mayer et al. 2021; Imhoff et al. 2004; Ma, Zhou, and Pei 2012). Estimates of NPP and HANPP can been extrapolated back in time, e.g., (Kohlheb and Krausmann 2009) or attributed to specific components of the global food system, e.g., (Roux et al. 2022), or attributed to trade flows (Liang et al. 2023) on such a basis. As another approach, estimates have been made at an increasingly granular scale using satellite imagery based on solar

[2] The changes in the value of intellectual property could, notionally, be included but would suffer from the same issues as GDP/capita experience due to Ireland's large, largely unintegrated, international business presence.

[3] Current guidelines at the national level are to apply a 4% social discount rate based on the social rate of time preference (SRTP) approach, declining to 1.5% over the very long term (>275 years) for long-lived considerations.

[4] Notionally, this is based on the expectation or future estimates of the growth rate of consumption. In practice, this tends to be based on recent growth rate, sometimes with minor adjustments.

energy absorption and similar assumptions on production and the functionality of ecosystem services (National Aeronautics and Space Administration 2023; Imhoff et al. 2004).

Additional indicators considered

In this appendix, we discuss the rationale for excluding certain promising indicators. Their recommendation across multiple sources influenced the selection of indicators. In particular, tier III indicator selection is influenced by their listing in other assessment frameworks composed of multiple indicators. The lists of indicators were first standardised and condensed where possible, following the methodology discussed in the main text. In addition to their listing in other frameworks, we required that the indicators apply to conditions in Ireland, be expected to vary within the country, and somehow relate to land use. On the final requirement, we did not initially require an expectation that land use changes would result in changes in the indicator, instead evaluating this later in the process. We took these steps to include the broadest possible set of potentially informative statistics. The current and future capacity for collection also did not enter the indicator selection stage but rather was performed as a separate step to ensure that data availability did not dictate indicator selection as 'what gets measured, gets managed' is a central guiding concept for this research.

Subsequently, some indicators were selected and then removed from our indicator set at a late stage. Those indicators are discussed here. Initially we included the Living Planet Index as an alternative option to IUCN Red List in the planetary boundaries of Tier II. However, the then focussed on the IUCN Red List as an index as an assessment of extinction risk to focus limited resources on the most pressing, irreversible issues for prioritising conservation efforts. In many ways, the Living Planet Index offers a broader, ecosystem-level perspective tracking trends in population abundance across potentially several species. However, this makes it less suitable when resources are constrained. This supports the framework being action oriented.

Aerosol Optical Depth (AOD) relate to atmospheric aerosol loading, a more encompassing measure of air quality, has been removed from the tier II indicators in the planetary boundaries component of this framework. While traditionally connected to land use, recent policy changes in Ireland, such as the banning of agricultural waste burning, have significantly reduced its relevance as a land-use-related indicator. Additionally, natural sources, such as sea mist, play a substantial role in Ireland's aerosol loading yet are unrelated to land use. This removal does not detract from the importance of other components, such as PM 2.5, but acknowledges that AOD in Ireland is now more influenced

by non-land use sources – particularly the burning of biomass for heating – than it is relevant to land use policy.

Indicators related to the marine environment, such as plastic debris density, fish stock status, fish landings, and the Coastal Water Quality Index (C-WQI), were initially considered for inclusion. These proposed indicators provide valuable insight into marine ecosystem health and its role as a substitute for land-based production, particularly for protein. However, after a review of their relevance to land use policy, these indicators have been removed to focus on land use outcomes, which can be attributed to specific land use changes and locations. Additionally, much of Ireland's fish stocks are either managed by the European Union via the Common Fisheries Policy (CFP) (implemented by the Department of Agriculture, Food and the Marine) or impacted primarily by international actors as the majority of fishing activity in Ireland's Exclusive Economic Zone (EEZ) is conducted by foreign entities. These are issues that cannot be managed by land use policy.

Yet, we note that increases in agricultural activity could reduce reliance on marine protein sources in Ireland, regardless of who harvests from Ireland's EEZ. Water quality near Ireland's costs will also be impacted by nutrient runoff from agriculture, even if attribution to specific locations is not possible – making it impossible to link C-WQI changes to changes at sites. Plastic debris density is also a vital indicator for tracking marine pollution and its impacts on ecosystems and human industries. However, plastic pollution originates from myriad global sources, primarily not tied to land use or even Ireland. However, an alternative perspective is to treat Ireland's EEZ areas as synonymous with land-based production, viewing fisheries management as parallel to agricultural land management. This integrated view would support holistic policymaking but would encounter constraints via EU management of fisheries and international marine pressures. Municipal solid waste generation and the solid waste recovery and recycling rates were also initially considered for inclusion as indicators. However, these metrics exhibit a weak relationship with land use policies. Instead, the causal relationship is likely reversed – increased waste generation may drive greater land use for waste processing and storage. As such, these indicators have been excluded to prevent waste-related land use impacts from influencing policy. However, we note that municipal solid waste generation and recycling rates, are relevant for understanding Ireland's progression toward a circular economy and reduced demand for landfills. These indicators highlight the environmental impacts of consumption and recycling behaviour, as does wastewater treatment as a critical issue for protecting Ireland's waterways – even if not primarily land use driven.

Issues with LULUCF monitoring

To understand how land use policy can be adapted to improve outcomes, it is also essential to measure changes in Land Use, Land Use Change, and Forestry (LULUCF) effectively. During our review, we have highlights some approaches, key components, and concerns about the state of LULUCF monitoring – many of which align with Phase 1 of the *Land Use Evidence Review* (O'Rourke, Byrne, and Smith 2023). CORINE land cover maps offer detailed mapping of Ireland's landscape on a 25-hectare scale, grouping land into artificial surfaces, agriculture, forests, seminatural areas, wetlands, and water (Büttner et al. 2021; Environmental Protection Agency 2018a). However, CORINE's six-year update cycle may miss rapid socio-economic shifts, though it can validate other datasets. Supporting those assessments, EAGLE land use attributes provide a structure for aggregating land use into primary, secondary, and tertiary production, infrastructure, and other uses (Arnold et al. 2023). Although Ireland's land mainly falls into agricultural production, finer-scale monitoring may provide better predictive power for linked socio-economic or environmental outcomes.

Indicators for protected status and land condition, such as Natura 2000, Ramsar Convention sites, and FSC/PEFC certifications, emphasise both biodiversity preservation and cultural heritage, with some measures suggesting preserving versus restoring to natural conditions – that the baseline for comparison may differ. Agricultural and fishery protections tend to recommend tracking organic, conservation, or high nature value (HNV) production which may not appear dissimilar during LULUCF assessments. As highlighted by MAES, the Irish National Biodiversity Indicators, the Aichi Biodiversity Targets, and the *Land Use Evidence Review*, metrics like the landscape mosaic index (Riitters, Wickham, and Wade 2009) would cluster land cover types to assess habitat fragmentation, yet species-specific land requirements complicate assessments as an aggregate indicator. Land take and biodiversity net gain (BNG) metrics also suggest measuring the dynamic nature of land use, in this case the conversion of natural habitats to human uses. We also note that wetlands monitoring is critical to addressing runoff risks from nearby agricultural areas, and conversely the value of wetlands to agriculture through ecosystem services such as water purification, flood hazard mitigation, and as a source of biodiversity. This suggests that interactions and spillovers between land uses are important yet may be difficult to capture via remote sensing.

Details of the case study of Ireland data collection

In this study, we identify their collection status in Ireland as to whether they are being collected, at what scale and frequency, and by which agencies, departments, or other interested parties. The inadequacy of data collection is a well-documented issue, with concerns underscored by initiatives like the commissioning of the *Land Use Evidence Review*. We find the current state of data availability to be disjointed with information from unrelated sources. We discuss this in relation to the three tiers of our proposed integrated framework.

Tier I indicator - GPI

There has been an unsuccessful history of trying to legislate the collection and reporting of a GPI in Ireland (Howlin 2017; Nash 2020). We can, however, assess the collection of data relevant to constructing the GPI. The recording of non-market goods and services consumption consistently at the household level is currently non-existent in Ireland. However, following initiatives to establish and then expand the system of environmental-economic accounting (SEEA) framework by the European Union (European Union 2011; 2022), the CSO has established an Ecosystem Accounts Division (EAD) for the purposes of monitoring and reporting on the extent and value of ecosystems in Ireland. Regulation No 691/2011 specified which ecosystem accounts must be monitored and specifies reporting on a three-yearly basis. Monitoring requirements include the extent of ecosystem types at a high level of typology (level one), the condition of ecosystems (nine variables) and the service flows from ecosystems (seven services). The European Union mandates the collection of the same data from each member country for comparability and so some variables will monitor more pressing issues in Ireland than others.

The CSO EAD's baseline assessments, once available in 2026 will contain information on the extent and condition in physical units relevant to environmental components of NCC and NMP. This might also build on work at the EPA on measuring the extent of some natural capital in Ireland, but not valuing it (Stout et al. 2023), advice on natural capital accounting in Ireland (Ní Dhúill and Sheehy 2024), the NPWS's ecosystem services mapping project (Parker et al. 2016), partial valuation frameworks such as (Norton, Hynes, and Boyd 2016), or the more developed national capital accounting framework used in the United Kingdom (Office for National Statistics 2024). The CSO EAD's current mandate, however, does not include the transformation of services into monetary value terms. If the CSO EAD later follows United Nations and European Union guidelines (European Commission et al. 2014; Vysna et al. 2021), a highly disaggregated accounting of ecosystem services in terms of value will result and could potentially be re-created based on historical data on ecosystem service flows. Estimates on non-market and public service flows might also be arrived at by

survey-based methods on the household level. These would require extensive collection on respondent use of such services and their interaction with the environment, both directly and via their consumption choices. This would also require information on the value of substitutes – the opportunity costs of their choices, or other valuation methods to place into comparable financial terms. However, these estimates are no closer to being available at this time than comprehensive SEEA estimates. It is also unlikely that reliable natural capital estimates can be obtained from household surveys alone due to the complexity of their measurement and value over time.

We also note that spending tied to adaptation and resilience is potentially considerable and is a means of including the costs of global climate change in measures of welfare. These costs would include spending under the Climate Action and Low Carbon Development Act 2021 (Government of Ireland 2021) such as €3.15 billion via the Future Ireland Fund and Infrastructure, Climate and Nature Fund Act 2024 (Government of Ireland 2024) and substantial transitions costs of €1-3 billion/year (Casey and Carroll 2023). The alternative to these expenditures is large reductions in income earning potential, the value of NMP and NCC components, and investments. These have conservatively been estimated as a reduction of €2 billion/year by 2050 (de Bruin, Kweku Kyei, and Henry 2024) - as this estimate does not include the value of ecosystem services.

Estimates of net changes in Ireland's built capital stock are, in comparison, at least nationally available. They are estimated annually as a component of national accounting (Central Statistics Office 2024f) following standard accounting practices. These estimates are available for a number of years in their aggregate form, and it may be possible to estimate disaggregated historical values. It is unclear, however, whether reliable, comparable estimates of human capital exist.

Overall, we find that Ireland is substantially unprepared to implement monitoring of a sufficient number of GPI components at a sufficiently granular scale to arrive at productive estimates. However, this is unlikely to remain the case as there is substantial interest within both Ireland and the European Union in establishing relevant monitoring frameworks. However, putting estimates in financial terms will also require a concerted research effort, even once the extent of ecosystem service flows and natural capital values are estimated in their natural units. As such, it is unclear when functional and meaningful GPI estimates will exist as these research efforts have yet to be established and would take some time to complete.

Tier II indicators

Compared to GPI, Ireland's collection of the domain summary Tier II indicators is proceeding well. The Central Statistics Office (CSO), as the country's primary statistical agency, collects and makes available some of the data on our indicators of interest. Data is primarily available through the CSO's data portal (Central Statistics Office 2024c), dedicated reports, Ireland's open data repository (Open Data Unit, Department of Public Expenditure NDP Delivery and Reform, 2024), and via international repositories such as Eurostat (Eurostat 2024).

Subjective well-being (SWB)

Subjective well-being (SWB) has been of increasing interest globally and within Ireland (OECD 2024; Department of the Taoiseach 2023). Compared to some measures, the measurement of well-being is more open to interpretation and innovation as it is a concept that has yet to converge to a fixed definition and methodology (O'Rafferty 2020). Rather, inter- and intra-temporal comparability is sought. As a component of statistics on living conditions, the European Union regulates the collection of metrics on well-being, e.g., (European Union 2003). Subsequently, the CSO included modules on well-being in the 2013 and 2018 Survey on Income and Living Conditions (SILC) (C. O'Brien 2018; Wall 2013). They have also collected limited data on subjective well-being annually from 2021-2023 (most recent data), which includes questions on the respondent's perceived standard of health. (Central Statistics Office 2024k). The CSO's SWB reporting is at the national level. However, reported sample sizes of 4,191 households and 10,199 individuals participated in the 2023 SILC (Central Statistics Office 2024j) suggests that county-level or more granular reporting on SWB and other SILC-based metrics is both feasible and the data may already exist internally at the CSO. In 2021-2023, the Irish Government published an annual report titled Understanding Life in Ireland: The Well-being Framework 2023, and the Framework consists of eleven dimensions of a sustainable quality of life, which were developed from 35 indicators. As of 2023, the government committed to a review of the Framework in approximately four years' time (Department of the Taoiseach 2023). The report includes a detailed methodology, which can be summarised as follows: a 100% improvement in an indicator over c. 5 years and/or Ireland is the best-performing country and constitutes a result of 1. Where performance is 0, there was no change over the last 5 years, and/or Ireland's score is the same as the average. Where performance is -1, this means there was 100% deterioration in the indicator over c. 5 years and/or Ireland is the worst performing country.

Income or product per capita

The closest equivalent to per-capita national statistics such as GNI are likely household, equivalised incomes. These income measures are adjusted by household size and placed in disposable or net rather than gross terms. The CSO, like statistical agencies in most countries, have collected such statistics for several years as a key metric in national policy decision-making, e.g., via the CSO's SILC since 2010 (Central Statistics Office 2024j). However, the most granular level public available is regional.

Ecological footprint relative to biocapacity accounts (EFBA)

Data on the ecological footprint relative to biocapacity accounts (EFBA) is not domestically collected for the purpose of constructing EFBA in Ireland. The data available in Ireland are based on national estimates as a part of a global database based on assumptions about the productivity of land types and consumption at the national scale (Dworatzek et al. 2024). Subsequently, consumption and biocapacity, placed in necessary per capita and per hectare scales, does not exist at this time. To match the existing EFBA methodology (Lin et al. 2018), this would involve granular, at least annually updated estimates of yield and equivalence factors across major land types. To match international estimates these would be on factors for infrastructure, forests, inland fishing, marine fishing, grazing, and crop lands. However, factors could instead be chosen to match Ireland's mix of land cover. These factors are then used to reflect the relative productivity of different land types for use in biocapacity accounting. Similarly, society's ecological footprint would need to be estimated on a similar granular scale and consistently updated. Existing EFBA national accounting basis the footprint component on a consumption land-use matrix (CLUM) relating consumption to different land uses/covers (Global Footprint Network, n.d.). Much of this data could conceivably be collected in the SILC, the Household Budget Survey if sample sizes were substantially larger (Central Statistics Office 2024g), or as a separate endeavour. Additionally, sectoral input-output tables (Central Statistics Office 2023c) would be used to account for the carbon footprint and other impacts of industry – and should also be updated over time. In short, a dedicated effort involving geospatial analysis and additional survey work will be needed to arrive at land use-relevant EFBA accounting. However, such an endeavour may yield significant results for policy development in Ireland as a disaggregated EFBA metric would be highly informative on the impacts of land use.

Climate change adaptation scorecard-based index

A climate change adaptation scorecard-based index would follow from the national-scale work by the Climate Change Advisory Council, which is now in its fourth iteration (Climate Change Advisory Council 2024). However, such a means of assessment would need to be redeveloped. It would need to be primarily quantitative in nature rather than qualitative as

the assessment would need to be conducted on a substantially larger scale to provide results that are meaningful relative to land use.[5] The assessment would then need to be conducted with departments, agencies, county, and city-level management to ensure sufficiently granular collection. This would clearly require substantial planning and an upscaling in capacity relative to the current endeavour.

Planetary boundary contributions

The EPA has made a significant effort to make data more publicly available including data relevant to Ireland's planetary boundaries contributions. This has included substantial data via their Geo Portal (Environmental Protection Agency 2024c), EPA's research data archive (Environmental Protection Agency 2024m) and via datasets on the open data repository (Open Data Unit, Department of Public Expenditure NDP Delivery and Reform, 2024). This information has enabled the EPA to conduct highly relevant and informative environment-focussed reporting (c.f., (Environmental Protection Agency 2024k). This has been supported by other efforts, including community and volunteer-based collected efforts in the context of biodiversity monitoring. Subsequently, in some cases substantial data is available but needs additional processing and management to place in comparable terms to land use. In this section we review data availability tied to SRC Planetary Boundary monitoring recommendations.

Greenhouse gas emissions (CO_2e)

The EPA has previously undertaken comprehensive geospatial modelling of greenhouse gas and other emissions of interest (Nielsen et al. 2020). However, most of the reporting on greenhouse gas emissions is at the national scale, divided by major sources. The frequency of reporting has recently changed to quarterly (Environmental Protection Agency 2024d) on a seasonally adjusted basis. The data itself is divided into sectors of agriculture, buildings, electricity generation, industry, transportation, and other. Estimates are placed in CO2e equivalent terms based on their global warming potential. Estimates are both available at the national scale since 1990 (Environmental Protection Agency 2024j) and projected to 2050 (Environmental Protection Agency 2024h). In both cases, these estimates are based on modelling the emissions impacts of several processes, including several focused on agriculture (Environmental Protection Agency 2024i). Subsequently, regional or more granular estimates could similarly be derived if the parameters of the EPA's models are known on a more granular scale. This data is not at present available, however, and may

[5] Improving the clarity of how the assessment is being conducted by making it quantitative in nature would also fit with recommendations from the most recent adaptation scorecard workshop (Climate Change Advisory Council 2023).

require substantially greater data on differences in the determinants of emissions across the country.

IUCN Red List

The IUCN Red List database lists 1680 entries for Ireland as it includes species found in Irish waters and migratory species that pass through Ireland. Subsequently, the monitoring of species abundance and diversity must rely on the domestic share of IUCN Red List monitoring. The baselines for assessment have been developed by the NPWS in the form of regional red-list reports (National Parks & Wildlife Service 2020). These are updated over a six-year as required by the Habitat Directive and focussed on specific groups of species. These efforts are complemented by several species or habitat-specific surveys published and NPWS Irish Wildlife Manuals on a comparable timescale (National Parks & Wildlife Service 2024).

Other efforts have also been undertaken to assess the status of Ireland's wildlife. These have often also focussed on specific groups of species. BirdWatch Ireland conducts primarily volunteer-based data collection on an annual basis. These include the Countryside Bird Survey since 1998 on breeding countryside birds during breeding season (BirdWatch Ireland 2024a), the Irish Wetland Bird Survey since 1994 which visits the same wetlands year-over-year (BirdWatch Ireland 2024b) and the Garden Bird Survey running through winters since 1989. The National Biodiversity Data Centre also operates several targeted monitoring programmes (National Biodiversity Data Centre 2024c). These include the Irish Butterfly Monitoring Scheme since 2008, Bumblebee Monitoring Scheme since 2012, the new Flower-Insect Timed Count, Dragonfly Ireland since 2019, Rare Plant Monitoring since 2017, several more targeted surveys (e.g., urban foxes, Irish hedgehogs), and a few marine biodiversity surveys (National Biodiversity Data Centre 2024a). As these survey endeavours are heavily citizen science-based – data collection is primarily conducted by volunteers – the data collected requires special treatment as collection is unlikely to be representative.

Our takeaway is that substantial data has been collected that can bridge the gap between the intention behind the IUCN Red List, and implementation at a subnational scale. However, the six-year interval of collection of some sources reduces our ability to link it to other outcomes. In other cases, citizen science-based data will also require specialised processing to account for the probability of observation (selection bias) to bring to statistical standards.

Net primary production (NPP) or Biodiversity Habitat Index (BHI)

Net primary production (NPP) is, in short, the net change in carbon biomass over time. It is sometimes discussed in terms of human appropriation of NPP, or HANPP. NPP and HANPP

then indicate two different trends. NPP is directly related to carbon storage, regardless of whether landscape changes benefit biodiversity. In comparison, HANPP indicates how much of NPP goes to human uses and conversely what remains to support biodiversity and the stability of the environment. However, when NPP is also subdivided by land use types, it remains more informative about biodiversity as well when, say, the NPP of agriculture is counted separated from that in wetlands. Ideally, NPP and HANPP would both be measured.

The use of remote sensing suggests that granular, comparatively low-cost estimates of NPP and HANPP can be derived. However, estimates are heavily reliant on their calibration to real world conditions. When the parameters representing conditions fundamentally change, e.g., reductions in the soil's ability to store carbon as the climate warms (Rodrigues, Brito, and Nunes 2023), estimates based on prior calibrations will become inaccurate. Subsequently, substantial fieldwork is required – both initially across Ireland and periodically updated – to support granular remote sensing based NPP and HANPP estimation. This sort of verification and linkage to remote sensing information has already been started, for example by the EPA (Saunders et al. 2022) and work on long-term soil carbon sequestration by Teagasc (Fenton et al. 2024; Teagasc, n.d.-a) in addition to traditional soil mapping (Teagasc, Environmental Protection Agency, and Cranfield University, n.d.). Additionally, using satellite-based sensing will limit NPP reporting to the frequency of collection and analysis. However, this will also be true for change in LULUCF which we would want to tie to outcomes. In conclusion, indicative estimates of NPP and HANPP exist for Ireland, but estimates of sufficient quality and granularity on which to base policy do not exist at this time and will require a concerted research effort to gather and update over time.

The Biodiversity Habitat Index (BHI) instead measures the suitability of a habitat relative to expectations. This would require determinations of what habitat should exist at each location, followed by determinations of the extent to which each location matches that expectation. As will be noted in the land cover share planetary boundary indicator, the first requirement has yet to be met which is a necessary precursor to the second, as habitats are far from homogeneous within summary labels such as wetlands.

Surface and groundwater NO_3 and/or P concentrations

The main issue impacting water quality in Ireland, like much of the European Union, is excess concentrations of nitrogen and phosphorus entering waterways, primarily from agriculture (Environmental Protection Agency 2024k).[6] Subsequently and in response to Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (European Union

[6] See chapter 8 of Ireland's State of the Environment Report 2024.

2000), Ireland has undertaken substantial efforts to monitor the status of Ireland's waters and begin remediation efforts. This effort has been further supported recently by the Water Action Plan 2024 (Department of Housing, Local Government and Heritage 2024).

Measurement of water quality in Ireland is well underway as the result of an expanding effort that started in the 1970s (Hannigan and Kelly-Quinn 2016). However, the monitoring of water quality requires a substantial effort, and it faces challenges in terms of integration with other data. The geographic unit of measure for water quality tends to be the catchment in Ireland where there are 46 catchments with 583 sub-catchments and 4,829 monitored water bodies (across rivers, lakes, estuaries, coastal and ground water). This is a subset of the about 84,000km of waterways, plus around 12,000 lakes and expansive coastline (Feeley et al. 2020). Subsequently, data on the water quality of Ireland is a subsample, albeit a substantial one. In addition to EPA's Geo Portal, research data repository, and contributions to Open Data, EPA publishes substantial data via (Environmental Protection Agency 2024b)However, data from the Geo Portal is perhaps most accessible. Groundwater quality data includes sufficient information for monitoring N and P concentrations as well as several other pollutants.

However, catchment monitoring also necessitates converting information into comparable geographic scales to land use. As pollutants are carried from one area to another, careful consideration of where pollutants enter waterways when attributing to land use is also required. This suggests additional research is needed on the scale to which the positioning of monitoring stations allows attribution – identifying where pollutants have entered Ireland's waterways in response to land use. In conclusion, a history of promising data collection has occurred, but it is unclear whether it is being collected in a way that informs on land use at a granular scale.[7]

Land cover shares relative to targets

Ireland has made admirable progress in LULUCF classification as part of the European CORINE land cover programme (Lydon et al. 2023). That effort, released in six-year intervals[8] is based on granular, primarily satellite-based imagery, supported by substantial secondary data sources on land use and land cover (to be released in three-year intervals in CORINE's

[7] In a complementary approach, the EPA established in late 2022 the National Agricultural Inspection Programme to inspect agricultural sources of excess runoff into waterways (Environmental Protection Agency 2024n). This involves reporting of point source operations and subsequently inspections by EPA, with a substantial number of inspected operations being fined to date. This sort of programme does not directly support identification, however, changes in the share of operations which excessively pollute in response to changes in policy is another potential, Irish context-specific indicator.

[8] mostly recently based on 2018 data with the analysis completed in 2022

replacement programme – CLCPlus). However, the frequency of data collection provides some hindrance in comparison to more high frequency socio-economic and production data.

However, the greater limitation may be in coming to some agreement on what land cover should look like and what land cover targets should be at a granular scale. Ireland has multiple, sometimes competing interests relevant to LULUCF. The Habitat Directive (European Union 1992) and Natura 2000 protection efforts (European Environment Agency 2023) have resulted in substantial planning studies and efforts (Environmental Protection Agency 2024g). However, some of these efforts may conflict with local and regional development plans to address socio-economic issues such as Ireland's housing crisis. Other programmes, such as the CAP, have adjusted in recent years to place a larger focus on environmental protection and conservation (European Commission 2022). However, to determine whether land use policy is positively affecting land cover shares, granular, multi-stakeholder agreed land cover targets are in order. If these exist, they are not publicly available. A concerted government effort is likely needed to arrive at such targets.

PFAS levels in surface and groundwater, particularly drinking water

As a signatory to the Stockholm Convention on Persistent Organic Pollutants (POPs) Ireland has obligations to reduce or eliminate POPs including many PFAS (United Nations Environment Programme 2023). However, PFAS – and POPs – can find their way into the environment and subsequently back into our food system by other, less deliberate means than their production and application. One potential source of PFAS exposure tied to land use is the application of biosolids from waste treatment facilities in agriculture. As these chemicals can accumulate in waste and are difficult to remove, monitoring has been focused on prevention of substantial flows into treatment facilities rather than any sort of attempt at removal from biosolids as part of the National Wastewater Sludge Management Plan (Uisce Éireann 2016). Ireland's POP National Implementation Plan notes that Uisce Éireann would monitor POPs but the results are not publicly available.

Ireland's POP National Implementation Plan further notes the limited monitoring of POPs – and by extension PFAS monitoring – in Ireland's soils (Environmental Protection Agency 2018b). However, the EPA has reportedly included major PFAS elements in surface water monitoring since 2019 as part of the Water Framework Directive in addition to some one-off studies (Environmental Protection Agency, n.d.). Reporting of individual measurements under the Water Framework Directive are not, however, publicly available and summary information has only been published in one-off reporting at the national level in terms of the number of sites exceeding guidelines (Environmental Protection Agency 2022). In terms of PFAS levels in groundwater, the EPA has undertaken to monitor levels at six-year intervals

following EU guidelines (Environmental Protection Agency 2023). To date, publicly available data includes 197 measurements in the year 2020 of 618 total borehole measurements. In conclusion, while monitoring is reportedly increasing, the level of data currently available is insufficient to determine whether PFAS is an issue in Irish soils or otherwise tied to land use at this time.

Tier III indicators

If there are shortfalls in measures of progress towards production, socio-economic, or environmental goals measured within Tier II, our assessment framework would then recommend using Tier III diagnostic indicators to identify causes of shortfalls in progress. Data sources for these indicators are sometimes related to additional analysis of Tier II data sources, but more often require independent data collection. The latter cases result in additional validation of conditions as the summary and diagnostic indicator result from separate sources.

Air pollution (CH_4, NH_3, and an AQI)

As noted in the Tier II indicators section, the Government of Ireland requires annual reporting on several greenhouse gas emissions, which was recently revised to quarterly reporting. (Environmental Protection Agency 2024d). Quarterly reporting is in the form of CO_2e, with annual disaggregated estimates following annually. These include methane (CH_4), the second largest greenhouse gas contribution to global warming from Ireland (Environmental Protection Agency 2024f). This is due to livestock in agriculture being the largest source of methane emissions and the basis of a substantial share of economic activity in the country.

The IPCC provides guidance on the estimation of greenhouse gas emissions, with a preference for the use of parameters estimated at a granular scale and frequently updated to capture changes in technology and interactions between factors. The general method for calculating methane (CH_4) emissions is attribution to specific economic activities, particularly related to livestock, agriculture, and land use. This would, for example, be based on a CH_4 emissions estimate per head of livestock – a multiplier. In the absence of more granular data, national estimates are generally applied to arrive at estimates. A more expansive version of this methodology is then used to arrive at national estimates in Ireland's National Inventory Submissions, e.g., (Environmental Protection Agency 2024i) , and past and future estimates available at (Environmental Protection Agency 2024h). The capacity to estimate these emissions at a granular scale will then depend on the availability of production data and developing and updating appropriate emissions intensity factors to account for regional variances. This would continue recent efforts to arrive at revised emissions factors commissioned by the EPA (D. O'Brien and Shalloo 2019) and on mapping greenhouse gas emissions at a detailed level (Nielsen et al. 2020).

Agricultural activity is also the source of nearly all ammonia (NH_3) emissions in most countries. Rather than contributing to global warming, NH_3 is an air and water pollutant with substantial negative impacts on environmental and human health. Because of their widespread negative impacts, as well as indicating inefficient production methods, decreasing ammonia emissions has received substantial attention. This has resulting in the inclusion of NH_3 in the National Emissions Ceilings Directive ceilings (European Union 2016) and estimates on how to best reduce emissions (Buckley et al. 2020) and revisions of estimates of emissions intensity factors (Owusu-Twum et al. 2024). Estimates of NH3 are also supported by recent mapping efforts, e.g., (Nielsen et al. 2020) and are similarly constrained by the availability of production data and disaggregated emissions intensity factors.

The outcome of several air pollutants of lesser concern could be modelled as a composite air quality index (AQI). National ambient air quality monitoring sites have expanded substantially in recent years to 115 sites which monitor air quality frequently throughout the day.[9, 10] This data is sufficient to arrive air quality estimates across the landscape in the form of an air quality index (AQI) (Environmental Protection Agency 2024a). As with some other estimates, e.g., water quality, there is some concern over ensuring attribution – that pollution is properly attributed to sources. The scale of AQI-relevant data also requires some thought on how best to arrive at an estimate – whether annual or seasonal means are preferable to estimates which report peak values or period of worse or best air quality.

Biodiversity (Biodiversity Intactness Index (BII), species richness, macroinvertebrate index on rivers, IUCN Red List status – disaggregated)

Tier II indicators on planetary boundaries included two dimensions on biosphere integrity – genetic diversity and functional integrity. Tier III indicators instead focus on collecting substantial information on the species in environments. These would then be reported in different ways – generally as indices – where the underlying data on specific species identified would be retained. This data could then support further diagnostic work based on the sensitivity of species to specific issues.

The Biodiversity Intactness Index (BII) would require the most in-depth knowledge on biodiversity as it measures the suitability of an area based on the average abundance of a

[9] In 2016, a European Union directive increase further the reporting requirement on a few critical air pollutants including NH_3 (The European Parliament and the Council of the European Union 2016) leading to the design of a national monitoring framework in Ireland (Kelleghan, David B. et al. 2021). However, this directive involves monitoring of air pollution on nature, focused on sensitive sites (Kelleghan et al. 2021).

[10] Ambient air monitoring may eventually include ammonia under a revised Cleaner Air for Europe Directive (Environmental Protection Agency 2024a).

substantial and diverse set of organisms relative to what we expected to be present in the area (Scholes and Biggs 2005). That is, it is a measure of species relative to a baseline expectation. This has been estimated globally based on geospatial analysis (Phillips et al. 2021) tied to estimates of species responsiveness to changes in habitats (Hudson et al. 2014). However, to make BII an operational component of policy at a granular scale would require local-scale knowledge that is sufficient to establish baselines for a variety of species, followed by careful monitoring.

Complements or alternatives have less stringent data requirements. Species richness is a count of species in an area without linking to a habitat baseline.[11] Substantial data has been collected on species observations in recent years via The National Biodiversity Data Centre's development of a citizen's science portal. This allows members of the public to report sightings of species throughout Ireland – over 1.3 million records to date – which can be accessed via their data portal (National Biodiversity Data Centre 2024b). However, as with other sources of volunteer data collection, careful study is required to account for the probability of sightings. A more rigorous, complementary approach would be to expand the frequency of NPWS's environmental inventory or survey work (National Parks & Wildlife Service, n.d.) as linkages to land use change will require repeated measurement on the same scale and timeline as land use change is observed.

Similar to species richness on land, the macroinvertebrate index suggests habitat suitability based on species abundance and composition. The EPA currently categorises river quality based on a "Q value" which is a classification of rivers into high, good, moderate, poor, or bad condition on the basis of macroinvertebrate samples as indicative of changes in the overall ecological status (Environmental Protection Agency 2020). Similarly, lake water quality is based on a wider sample of aquatic life (plants, phytoplankton, macroinvertebrates, phytobenthos, and fish) (Environmental Protection Agency 2024p). Water quality data collection in Ireland presents a substantial challenge due to the breadth of waterways. River water quality monitoring involves site visits for collection, with around 1,500 of 2,365 waterways assessed in 2022/2023 plus 224 lakes in 2021-2023 and several estuary and coastal sites for levels of key pollutants. As such, substantial data to inform a macroinvertebrate index exists with it dating back to the 1970s for some sites. However, work remains to be done on determining attribution to determine which land and water sources of runoff are impacting macroinvertebrates at each collection point. The suitability of current collection locations would then follow in this context from their efficacy in

[11] The Living Planet Index is a frequently noted alternative to species richness. This is a subset – a focus on counting only vertebrate species – as a generally more observable subset. This is a possibility worth considering if environmental surveying budgets are particularly constrained.

determining areas of land impacts biodiversity and waterway health. We also note substantial work monitoring the abundance of species in waterways by Inland Fisheries Ireland under the Water Framework Directive (European Union 2000). This has resulted in surveys of rivers, lakes, and transitional waterways annually since 2008 (Inland Fisheries Ireland 2024b) in addition to inland fisheries focussed reporting such as IFI's fish counter reports, e.g., (Inland Fisheries Ireland 2024a). This data would ideally be collated with the macroinvertebrate index and other data on the status of biodiversity in water.

Finally, as noted in the discussion of the IUCN Red List as a planetary boundary indicator, substantial subsets of species data have been collected in Ireland through citizen science initiatives of the NBDC. Whether these subsets are sufficiently indicative of environmental pressures due to land use change – or whether other disaggregate subsets should instead be monitored – warrants further consideration. Disaggregation of the IUCN Red List is also linked to the NPWS's six-year interval and additional one-off environmental survey work which may need to be upscaled.

Climate change (Carbon intensity of land use, government preparedness for climate change – public survey, Climate Adaptation Action Plan implementation).

The Government of Ireland recognises the importance of land use in mitigating global climate change as some land uses are substantial sources or sinks for greenhouse gases (Environmental Protection Agency 2024e). Differences in greenhouse gas emissions due to different land uses has resulted in the EPA modelling separately the emissions from agriculture, buildings, electricity generation, industry, transportation, and other uses (Environmental Protection Agency 2024l). Within these broad categories, emissions estimates are arrived at by modelling specific emissions generating processes, e.g., the impact of manure management practices on CH4 emissions. Emissions projections also include LULUCF changes (Environmental Protection Agency 2024h). As in the case of CO2e estimates, it is at present uncertain the additional capacity required to disaggregate national-scale estimates by land use type into granular estimates. However, disaggregated estimates by land use type would be important in identifying specific sources of excess emissions and so the development of this potential is highly recommended.

In addition to monitoring statistics relevant to mitigation, we have also recommended adaptation-related monitoring. Tier II indicators included an expansion of the CCAC's adaptation scorecard to capture the government's own perception of adaptation. To complement this, an expansion of current public survey efforts may be in order. For example, the CSO's SILC could include questions the public's perception of national preparedness for climate change and extreme weather events. This would ostensibly capture otherwise unknown shortfalls in adaptation efforts.

Reporting on climate change adaptation plan implementation would also support identifying shortfalls in preparation. The National Adaptation Framework (NAF) (Department of the Environment, Climate and Communications 2024) includes monitoring by local authorities in addition to national departments and agencies and so when implemented, the necessary data will ostensibly be collected.

Production (Agricultural yield (per hectare), timber production (forestry), urban land productivity (e.g., real estate and services), industrial land productivity, wetland ecosystem services, grassland productivity, recreational land use (parks, conservation areas))

Data on agricultural yield per hectare is collected by Teagasc on an annual basis as part of their EU Farm Accountancy Data Network membership requirements (European Commission 2024), national farm survey (NFS) reports (Teagasc 2024b) and harvest reports, e.g., (Teagasc 2024a). This data is often available at the regional (NUTS3) level in NFS reports – in some cases aggregated to the national level due to sample size issues – but is collected across Ireland.

The Department of Agriculture, Food and the Marine (DAFM) publishes the national level of forestry production in cubic metres on an annual basis as well as substantial, detailed statistics on the type of production (also aggregated to national statistics) and mapping of Ireland's forests (Department of Agriculture, Food and the Marine 2024). The CSO conducts the Roundwood Removals Survey to compile statistics on removals of roundwood and roundwood biomass from privately-owned forests in Ireland (Central Statistics Office 2023b) - also only publicly available as national statistics but data comes from respondents across Ireland.

It can be complex to measure urban land productivity and proxy variables may be required. For example, the CSO reported quarterly 2018 and 2019 data on employment rates in urban areas and they collect annual income and poverty rate data as part of the annual Survey of Income and Living Conditions (Central Statistics Office 2020). Another approach is to measure the share of urban land efficiently used via remote sensing. This would entail estimating the current composition of land use in urban areas versus benchmark land use or similar measures (O'Driscoll et al. 2023). This would place urban land use on a similar scale and concept for humans as BHI is to nature. An alternative, lesser information option would be to estimate used and occupied area to total area, though what is considered land well used, e.g., green spaces, would need to be decided anyway.

The CSO also collects quarterly data on employment by sector which includes industrial sectors which may represent industrial land productivity. Assessing the incomes of households in urban areas is also an option. A measure of production, or economic output, that is a direct result of the use of industrial land would be more informative, but this data is

not currently being collected. It might entail, for example, comparing the economic output of industrial land to the total consumption of natural resources – land plus ecosystem services – or, as a starting point, area of land used.

The value of wetland ecosystem services is likely substantial across Ireland's more than 13,500 wetland sites (Wetland Surveys Ireland 2024). Wetlands provide substantial value through provisioning, regulating, supporting, and cultural services. They both absorb and store water – purifying it, providing a source to draw from, and mitigating flooding. They also provide recreation and tourism opportunities, a habitat for biodiversity, and can either be a source of carbon emissions when or highly effective means of long-term storage, when effectively managed. Despite the extensive value that wetlands likely provide, estimates on their value are nearly non-existent and would require a substantial research effort to quantify and monitor.

Grasslands serve an important role in Ireland's food production as the largest share of agricultural land. Measuring their productivity is then of substantial importance to other agricultural operations as well as socio-economic outcomes through food and the cost of living. Subsequently, indicators of grassland productivity should enter an assessment framework alongside other agricultural yields. Monitoring of grass productivity, however, is complicated by grazing throughout the season and so requires more intensive monitoring. Teagasc collects detailed productivity data via the enrolment of producers in their PastureBase programme for the purpose of improved farm advising (Teagasc 2021). This is a substantial sample of grassland users which is not publicly available. For the purposes of monitoring grassland productivity, arriving at an agreement to use granular summary data would perhaps be the most expedient, efficient course of action. Alternatively, the CSO has produced summary national estimates of grassland production from 2000-2022 (Central Statistics Office 2024e) which are partially based on data provided to the CSO by Teagasc.

Recreational land use in Ireland is also a substantial source of value to both the public, including reducing healthcare costs via prevention, and a source of income from overseas tourism (Department of Rural and Community Development 2022). Fáilte Ireland survey national attractions on an annual basis and from that they can determine the number of people who visit natural attractions, visitor gardens, heritage sites, etc. (Fáilte Ireland 2024a). Such data is attraction specific.[12] Coillte also collect data on the numbers of visitors to their public forests (Coillte 2021).

As with other indicators, production indicators would perhaps be best fit for purpose if put on a common basis, e.g., euros of benefit per hectare. However, some land uses are non-

[12] A dashboard of this data is available at (Fáilte Ireland 2024b).

interchangeable, e.g., the extent to which wetlands and industrial areas can or should be transformed. As such, these benefits should not be considered comparable between land uses even if placed in the same units of measure. We would, rather, treat land cover shares, measured as the extent of land cover, separately as a planetary boundary indicator and then in our Tier III set further expand as we have suggested on the productivity of land uses.

Socio-economic (Discretionary income, Employment in agriculture, forestry, and other sectors, Access to services and infrastructure)

Data on disposable income is collected annually by the CSO as it is considered an important indicator of whether households are becoming better off or worse off (Central Statistics Office 2024h). This CSO data has been publicly available at the county scale since 1999 (Central Statistics Office 2024b). In recent years (2022 onwards), the data shows promise in being revised into a substantially more granular scale as estimates are based on employee tax, Department of Social Protection demographic, and CSO Business Register data which are matched before being anonymised (Central Statistics Office 2024d)

Employment from land use activities can be assessed from CSO labour force survey data which calculates 'agriculture, forestry and fishing' employment quarterly since 1998, with an improvement in methodology in mid-2017 (Central Statistics Office 2024i)This data is reported as an aggregate category based on a survey (12,863 valid responses in the first quarter of 2024) in which respondents were asked their industrial sector of main employment. As such, it is unclear whether further disaggregation of the data is possible.

In 2019, the CSO published a comprehensive report on the distance people travel to services such as schools, hospitals, garda stations, libraries, hospitals, public transport options, etc. This involved matching the coordinates of dwellings enumerated in the 2016 Census, the coordinates of destination points for a set of everyday services and the road network from Ordnance Survey Ireland (Central Statistics Office 2019a). The Census is conducted every 5 years (Central Statistics Office 2024a) and so, presumably, access to services can be updated via this method at that interval. Other data, such as travel times to work, have been asked on other regional quality of life surveys, e.g., (Central Statistics Office 2019b). Satisfaction with access to services and infrastructure could also be directly surveyed, building on the National Transport Authority's annual survey work, e.g., (National Transport Authority 2024), to encompass satisfaction with access to all services and infrastructure influenced by land use constraints.

Soil (Soil organic matter, erosion rates)

As a component of accurately estimating NPP, changes in soil carbon stocks across Ireland must be accurately estimated. If NPP is implemented within the Tier II indicators, then soil carbon estimates must be collected. If instead, the BHI is implemented due to weaker

collection requirements, soil organic matter estimation should proceed at intervals matching LULUCF collection. Work underway by the Geological Survey Ireland and Teagasc based on soil samples from the Tellus Project Ireland's soils (Geological Survey Ireland 2024a) have been used to identify soil carbon content.[13] This includes national mapping (Geological Survey Ireland and Teagasc 2024) and an in-depth study of farm soil content as an avenue for carbon sequestration (Geological Survey Ireland 2024b). This provides a baseline on soil organic content which would require some sort of programme to update when land use or climatic changes are expected to change soil organic matter content. Importantly, as the European Union mandates the collection of soil carbon content in some ecosystems (croplands and grasslands), the CSO EAD has a reporting requirement on a three-year interval (European Union 2011) with baseline estimates expected in 2026.

Model-based estimates of erosion at a course scale have previously been derived within Ireland (Kiely et al. 2014; Eurostat 2020; Joint Research Centre - European Soil Data Centre 2024). However, ground-based soil erosion[14] estimates are not directly reported in Ireland. However, turbidity as well as water content disaggregated is available as surrogates for total suspended solids. This data would conceivably need to be linked to land use through a similar attribution scheme to that proposed for other waterborne pollutants and then equated to erosion rates.

Water (Wastewater treatment efficiency, Water Quality Index (WQI))

As noted in the methodology section, nitrogen and phosphorous concentrations (NO_3 and P) in surface and groundwater are included in the planetary boundaries component of the Tier II indicators. In this section, we explore two additional recommended indicators. The first is the water quality index (WQI), and the second is wastewater treatment efficiency.

As noted, the EPA currently categorises inland waters using a Q value based on sampling macroinvertebrates. The macroinvertebrate index is clearly an important means of monitoring the net effect/overall health of Ireland's waterways. We have also noted that it is a useful count of the status of biodiversity in water. It could also conceivably function as a Tier II indicator if we included one specifically on inland waterways. However, macroinvertebrate composition and its lake equivalent do not function as efficiently for diagnostic purposes in terms of water quality as macroinvertebrates are likely impacted by nitrogen, phosphorous, and a variety of other pollutants which then cannot be isolated. Rather, a water quality index based on the pollutants themselves is more informative. The minimal necessary data to arrive at a composite pollutant index is available from the same

[13] Additional work by Teagasc aims to understand carbon uptake by soils using 28 study sites across Ireland (Teagasc, n.d.-b). This might inform a weighted value of carbon uptake for different soil types.

[14] For example, reported as total suspended solids at water monitoring station

source as nitrogen and phosphorous level data, e.g., EPA's Geo Portal (Environmental Protection Agency 2024c). However, the WQI would face the same issue of attribution.

Wastewater treatment and release is a distinct issue from agriculture and industry-based effluents – even if we were to focus on land use-based pollution, the inclusion of data on the location of wastewater releases would be important to separate out the impact of these flows from other issues. EPA publishes data on wastewater treatment and releases into the environment (Environmental Protection Agency 2017).[15] However, it is clear from reporting (Environmental Protection Agency 2024o), that Ireland continues to be substantially out of compliance with the European Union's Urban Wastewater Treatment Directive (European Union 1991).

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[15] This data is perhaps outdated – circa 2010 or 2017 – depending on the accuracy of the published metadata.

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