

Potential development of Irish agricultural sustainability indicators for current and future policy evaluation needs

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Highlights

- Reliable indicator provision is data intensive
- Multi-disciplinary approach improves indicator definition and provision
- Indicator development achieved via novel research, technology and secondary data
- Need to balance rigour, feasibility, representivity and continuity

Abstract

There is a significant and detailed range of sustainability indicators for Irish agri-food production, but there remain areas where further indicator development or new indicators could prove valuable. This review provides an outline of potential developments in Irish assessment of agricultural sustainability following the latest research and in order to meet policy demands. Recent research findings have suggested means of improved quantitative modelling of greenhouse gas emissions, but additional dietary and soil data may be important for this, especially for the potential inclusion of any soil sequestration. This information could also benefit more detailed modelling of nutrient losses to water. Specific concerns over pesticide and antibiotic use may require additional survey work on the particular locations or types of farms of interest. Biodiversity monitoring could be improved by expanding the range of results-oriented agri-environment schemes or employing remote-sensing habitat monitoring, likely supplemented with targeted field surveys for specific objectives. Farm-level economic sustainability is largely well-covered, but additional data collection may be of benefit to address specific issues such as labour costs. Recent additional surveys on farm-level social sustainability have addressed important social indicators of isolation and access to local services, and could be rolled out on a larger number of farms in the future. Wider societal concerns such as animal welfare, genetically modified materials in foodstuffs and antibiotic resistance have limited indicators currently available, and could also benefit from additional survey. The breadth and detail required in agri-food sustainability indicators present a significant challenge to survey design and implementation, but many developments can be achieved without additional surveys through the use of remote sensing and geospatial technologies and integration of existing datasets. Despite the important benefits of further developments in Irish sustainability indicators, consideration must also be given to farmer confidentiality and survey fatigue.

Keywords: Sustainability, agriculture, environmental impacts; economic sustainability, social sustainability

Introduction

Sustainability is an essential consideration in agricultural policy. In recent years, a number of studies have suggested potential indicators of agricultural sustainability, discussing indicator selection and

development and considering how these indicators should be interpreted (Bockstaller et al., 2009, Lebacqz et al., 2013, Latruffe et al., 2016). Despite this research attention, the large-scale deployment and on-going development of such indicator programmes has rarely been considered. In this paper we address this gap by describing some of the complexities of putting detailed agricultural sustainability indicators into practice, demonstrated in the Irish context. The paper provides a review of recent developments in the monitoring of agricultural sustainability and should prove useful to researchers and agricultural stakeholders involved in designing programmes to meet and exceed policy requirements. As there are few comprehensive overviews of working indicator programmes, this paper also aims to establish a framework and evidence base which can be used to build the capacity for similar indicator developments. In line with the considerable research and policy attention directed at the environmental pillar of sustainability, much of this paper addresses this topic, however we also consider means of assessing economic and social sustainability to provide a full appraisal. The relative size of each section is not intended to reflect differences in the importance of each pillar.

All three main sustainability pillars (environmental, economic and social) must be considered for a true sustainability assessment (Lebacqz et al., 2013, Latruffe et al., 2016). While each pillar is important in its own right, even if approaching agricultural sustainability with an environmental focus it is important to have a systemic approach that reveals linkages between different aspects of sustainability. Potential synergies, such as a link between greenhouse gas emissions efficiency of production and farm profitability for dairy farms (O'Brien et al., 2015), may help communicate and encourage uptake of environmentally beneficial practices. For many environmental impacts potential associations with economic or social issues are unknown, and so having a holistic sustainability assessment may prove important to identify any unintended trade-offs between different aspects of sustainability, to design and implement a successful environmental policy, or to interrogate the wider context of why environmental actions may not have been adopted.

In Ireland, the government and agri-food industry hope to realise ambitious growth targets up to 2025 and beyond (DAFM, 2015), and the sustainability of Irish food production is a key component of this strategy. There are, however, concerns about whether this growth can be achieved while minimising negative consequences (Wall et al., 2016). A range of detailed sustainability indicators will be needed to measure these potential impacts. As a European Union Member State, Ireland must also conform to European environmental legislation on, for example, water quality. Such legislation can entail specified sustainability indicators and/or direct indicator development to better drive policy compliance.

There is already a robust collection of indicators to assess the performance and sustainability of the Irish agri-food industry (Kelly et al., 2018), involving a number of stakeholders and programmes (see Table 1 for an overview of the most significant). However, several indicators could benefit from further development or data collection, and a number of relevant topics are not covered at present. This study describes the potential for new and/or improved indicators, including their scientific, policy or industry relevance, the possible means of indicator development, and data requirements. The focus of this review is to highlight opportunities to continue the development of indicators of agricultural sustainability in Ireland, which will also be of wider interest. Depending on the indicator, development may involve improved modelling of current indicators using already available data, expanded data collection in existing survey schemes, or additional surveys for certain sectors or farms of interest. We describe current best practice and discuss emerging issues, but do not intend this to be an overview of research needs or opportunities (although the indicator developments described could also benefit research).

The content covered in this paper, outlined in Table 2 below, is the result of a review of the current Irish agricultural sustainability programmes and consultation with a range of stakeholders about the indicator strengths and weaknesses, and priority areas for their improvement. Stakeholder consultations were held across 2016 and 2017, and included representatives from the Irish government, business groups, and the research community (key individuals are thanked in the acknowledgements below). Based on these consultations, literature reviews were undertaken on the topics identified, building on discussion with other researchers, the authors' own expertise, and citation mining of existing work on agricultural sustainability.

Greenhouse gas emissions

Current recording schemes and coverage

Ireland is a party to international policy commitments to reduce annual greenhouse gas emissions, with binding emissions targets under the EU Effort Sharing Decision. Emissions reductions are set at national rather than sectoral level (with a distinction made for emissions generated in the production of energy, which are instead handled under the EU Emissions Trading System), but as agriculture is responsible for a large proportion of Irish emissions, it might be expected that the sector will be required to make reductions (Lynch et al., 2016a). Here, potential improvements to greenhouse gas emissions methodologies are considered until the point at which agricultural produce leaves the farm gate. Although further emissions may be incurred in food processing and distribution, and there is also interest in tracking and reducing these emissions in the Irish agri-food industry, consumer attention and the most pressing policy concerns focus on emissions associated with agricultural production rather than emissions accrued post farm-gate.

Farm-level greenhouse gas emissions are currently estimated as part of the Teagasc National Farm Survey (NFS), which fulfils Ireland's submission to the EU FADN (Farm Accountancy Data Network) and the Bord Bia Origin Green Quality Assurance (QA) schemes. Data are available to give robust farm-level estimates for cattle and sheep systems following IPCC (Intergovernmental Panel on Climate Change) and certified LCA (Life Cycle Assessment) accounting conventions (the distinction between these methodologies is returned to below). The Bord Bia QA schemes aim to cover 100% of products exported, with 49,000 beef farm and 13,000 dairy farm assessments performed as of 2016. The Teagasc NFS covers approximately 900 farms annually, representative of 82,000+ nationally, including a considerable proportion of farms not covered by QA schemes (25% of the sample in 2015).

Further data relevant to agricultural greenhouse gas emissions are also collected through the Teagasc - Bord Bia 'Carbon Navigator' (Murphy et al., 2013), a decision support tool highlighting the potential gains in farm profitability and emissions reductions if certain key management practices are undertaken. The Carbon Navigator is a requirement of the on-going Beef Data Genomics Programme (BDGP), through which funding is available to cattle farmers, and is linked with data collection for the Bord Bia QA schemes.

A recent Teagasc NFS report has also estimated greenhouse gas emissions for a survey of 180 small farms (less than €8,000 output), representing a further 35,000 cattle and sheep farms nationally (Dillon et al., 2017a). Across these programmes there is therefore good coverage of dairy, beef and sheep production systems. Data collection that could be used in the estimation of emissions from pig, poultry and arable farms has yet to be implemented in the Bord Bia QA schemes, but is expected to follow in coming years. Arable farm emissions are generated as part of the Teagasc NFS, but at present specialist poultry farms are not collected. Although pig farms have recently been included in the NFS, environmental metrics are not currently generated for these farms. The systems that are accounted

for represent the majority of Irish agricultural greenhouse gas emissions (Duffy et al., 2017), and the potential improvements discussed in this paper focus on additions to current emissions estimate methodologies rather than covering additional systems. However, other sectors should be acknowledged and incorporated where feasible.

Further developments in greenhouse gas methodologies

Before describing specifics, it should be noted that many of the potential improvements described below cover ammonia as well as greenhouse gas emissions. Though not a direct greenhouse gas, ammonia is an important pollutant in its own right with strict limits under the European Communities National Emissions Ceilings Regulations, and is an important component of greenhouse gas methodologies as both a potential precursor to the greenhouse gas nitrous oxide, and a source of nitrogen losses influencing other greenhouse gas calculations. Improvements to ammonia inventories should therefore not be considered separate to improvements in greenhouse gas emissions methodologies.

Further detail on livestock emissions

Ruminant livestock enteric fermentation and emissions resulting from animal manures and slurries account for the majority of agricultural emissions in Ireland (Duffy et al., 2017). These are modelled based on animal diets and productivity (animal growth rates or milk production) in order to estimate methane emissions and excreta per animal, and the fate of animal manures to estimate the emissions resulting from excreta. National standard coefficients as described in the Irish National Inventory Report (Duffy et al., 2017) can be used to estimate these details per animal, but it is more powerful if the relevant data are available on a farm and even animal specific basis.

For cattle systems the necessary feed data are collected through both the Bord Bia QA schemes and the Teagasc NFS. Outputs are obtained by using creamery data on milk production for dairy farms and detailed livestock weight data are available through the ICBF (Irish Cattle Breeding Federation) database. This database is linked to the Bord Bia QA schemes, and there are plans to link this to the Teagasc NFS in the near future. A series of equations are used to calculate emissions and excreta based on animal energy demand (a function of livestock type and status, milk production, and weight changes) and feed (including feed digestibility, dry matter content and nitrogen content), following O'Mara (2006). On-going work should build on this to collect similar data and integrate these types of models in further systems.

There is a potential avenue for improving the dietary inputs through additional pasture data collection. At present, models assume energy intake from grass (or other forage) by deducting other directly recorded feeds from total energy demand (as described above). The energy content, dry matter, organic matter and digestibility of grass take the standard values defined in O'Mara (2006). This approach potentially misses some further differences between individual farms, or improvements in grassland management since the values were derived. Collecting further data on pasture production and linking it with wider agricultural performance data could also be linked to on-going initiatives highlighting grass utilisation, such as Grass10: Grassland Excellence for Irish Livestock (<https://www.teagasc.ie/crops/grassland/grass10/>). While direct collection of grass data is beyond the scope of current recording schemes, data could be obtained by linking with emerging external resources, such as satellite data (Ali et al., 2016) or the 'Pasture Base' grassland management decision support tool (Hanrahan et al., 2017). At present these databases can already provide grass growth estimates in terms of dry matter production and could be further developed to include species

composition, with the potential for further modelling of, for example, overall digestibility and nitrogen content of feeds.

Further data on animal excreta collection and fate could provide additional detail in emissions estimates, either building on dietary-specific excreta estimates outlined above, or based on standard values for different livestock. Different emissions factors are used depending on whether excreta are collected as liquid slurries, solid manures, or excreted directly to pasture (pasture emissions and emissions following application of stored manures are discussed further below). The most significant management data from which these details can be derived (housing and turnout dates, slurry and manure storage facilities) were originally collected in a 'Farm Facilities Survey' in 2003 (Hyde et al., 2008), and are now routinely collected by the Teagasc NFS and as part of Bord Bia QA schemes, but there is little collection of other relevant data. Livestock excreta on concrete yards can contribute significantly to greenhouse gas emissions and ammonia (Misselbrook et al., 2001), and the management of this excreta, for example whether they are scraped down or washed, can result in significant reductions in these emissions (Misselbrook et al., 1998).

Research has also shown the impacts of different slurry additives on GHG emissions, with increases or decreases depending on the additive (Brennan et al., 2015). There is also on-going research into the impacts of slurry mixing and/or aeration on emissions (Calvet et al., 2017). It would possibly prove too onerous to attempt to record all of these details within the current whole-farm survey schemes, but as the implications are potentially significant, a further farm facilities survey expanded in sample size and built on these more recent research findings could be beneficial.

Agricultural soil derived emissions

Emissions from agricultural soils include nitrous oxide emissions directly from soils, and from ammonia losses to the atmosphere or aqueous environment which later give rise to nitrous oxide. These are calculated based on nitrogen inputs to soil from synthetic fertilisers, sewage sludge, animal excreta, crop residues, soil nitrogen mineralisation, and drainage of wet organic soils. In addition, carbon dioxide emissions from liming and urea application are calculated based on the quantities of these inputs applied. Recent research developments in several of these areas are considered below.

Emissions resulting from livestock excretion on pasture are typically calculated by multiplying nitrogen inputs in excreta (further highlighting the relevance of strong livestock dietary data) by a small number of generic emissions factors, following IPCC guidelines (IPCC, 2006). Observed livestock excreta emissions were recently shown to be below default estimates for most conditions in Ireland (Krol et al., 2016), resulting in new emissions factors that reduced total agricultural nitrous oxide emissions estimates in the most recent (2018) National Inventory Report. There is also potential to link currently collected livestock excreta details with geospatial data on soil type (including, e.g., influence of recent weather) to cover additional complexities revealed in research. Emissions from livestock dung were also shown to be significantly lower than emissions from urine, with the potential for dietary changes or supplements to increase the nitrogen excreted in dung compared with urine (Krol et al., 2016). Continuing to collect relevant feed information and building the capacity to model any emissions changes resulting from the separation of urine and dung in excreta models can ensure that the benefits of such dietary interventions are recorded, without necessarily entailing extra survey effort.

Emissions resulting from the application of animal manures and slurries can build on details of excreta collection and storage discussed above. It is assumed that nitrogen contained in excreta that is not lost in gaseous form during animal housing or manure management is applied to agricultural soils, reinforcing the need to maintain an understanding of animal diets and manure storage facilities. The

influence of slurry additives discussed above in relation to emissions during storage can also determine emissions when applied to soils (Brennan et al., 2015), highlighting the relevance of collecting these data if slurry additives are widely adopted. Upon application, the method and timing of slurry delivery can also significantly influence emissions (Webb et al., 2010). Relevant slurry application data are already recorded in the Teagasc NFS and Bord Bia QA schemes, so rather than further data recording, potential developments may come through linking with additional management and geospatial data.

One area where current data are not especially strong is the transfer of manures and slurries between farms. Although imported slurries are recorded in the relevant survey programmes and are also recorded for Department of Agriculture monitoring, there are some concerns over the accuracy of slurry transfer volumes. In addition, a lack of detail in slurry transfers reduces the ability to model its nitrogen content and potential interactions with external datasets in improving emissions estimates. To date, a number of studies using the Teagasc NFS nitrogen input data have excluded farms importing or exporting slurry (e.g. Buckley et al., 2015), as this only accounts for a small proportion at present (8% of the NFS sample in 2015), but is an area for potential improvement.

In common with animal excreta emissions factors, experimental work has improved the understanding of emissions resulting from application of synthetic fertilisers in Irish conditions. The current default estimation of fertiliser based emissions assume a single emission factor of 1% loss for all nitrogen fertiliser inputs (IPCC, 2006), but recent studies demonstrate that typical emissions are lower than this for urea, but may be higher for calcium ammonium nitrate (CAN) (Harty et al., 2016), with new emission factors based on this research in the 2018 Irish National Inventory Report. Fertiliser emissions may also be influenced by soil type and drainage, but further research and more detailed activity data would be required to include this interaction in emissions estimates. For example, in typical Irish spring barley cropping systems (generally free-draining soils), emissions from CAN were found to be less than half the default emissions factor (Roche et al., 2016).

Both the Teagasc NFS and Bord Bia QA surveys record a breakdown of different fertiliser formulations, so could potentially provide activity data for the new emissions factors as supported in the scientific literature, and could be linked with extra soil and/or system data to generate improved emissions estimates. The necessary soil data could come through linking to geospatial datasets or by incorporating the results of farm soil tests. Recent research has also demonstrated potential reductions in emissions from urea by the addition of nitrogen stabilisers (Harty et al., 2016). While continued investigation is necessary to appraise their cost-effectiveness, environmental fate, and potential for residues to enter the food chain before a full appraisal of their use is made, it is recommended that surveys begin to include these fertiliser additives, as they are already commercially available (for example, NPBT, N-(n-butyl) thiophosphoric triamide, coated urea).

Advances in precision agriculture may also reduce fertiliser emissions by improved targeting of fertilisers (Snyder, 2017). At a whole-farm nitrogen balance level (discussed further below in terms of losses to water) these improvements should be revealed through lower total fertiliser applications, or more output per unit of fertiliser applied, without the need for extra data collection. If farm specific or even field and sub-field specific changes in emissions due to precision fertiliser targeting are to be incorporated in models or national emissions factors, they may require additional surveys to establish the uptake of these technologies, and/or access to farm management data on spatial and temporal variation in fertiliser applications and environmental conditions. These could potentially be shared if farmers agree to share access to relevant software and/or industry databases, but is beyond the scope of current data collection.

Potential inclusion of agricultural carbon sequestration

The potential for temperate grassland soils to sequester carbon is well recognised (Jones and Donnelly, 2004). In Ireland this is notable due to the prominence of agricultural greenhouse gas emissions in national policy debate, and the significant area of permanent grassland already potentially sequestering large quantities of carbon (RIA, 2016). Yet the soil carbon stock is also expected to saturate in the long-term, and without appropriate management soils can also risk becoming a source of emissions (Smith, 2014). There is currently no universally accepted method for estimating changes in soil carbon stock in permanent grassland, despite the potential importance of these fluxes in life cycle assessments (e.g. O'Brien et al., 2016).

The Food and Agriculture Organisation of the United Nations (FAO) Livestock Environment Assessment and Performance (LEAP) Partnership have recently published draft guidelines for estimating soil carbon stock changes (FAO, 2018) that may overcome some of these issues. Keeping the Irish methodologies up to date with these guidelines and basing any further data needs upon them would be advisable, in order to include grassland carbon sequestration in a justified manner in line with international best practice. Further soil data collection may be advised as part of current programmes or in extra, one-off, surveys. Linking farm management data to geospatial datasets may also provide a powerful means of collating the necessary information, in common with other topics described above.

In addition to carbon sequestration through agricultural soils, there is continued interest in Ireland in off-setting agricultural emissions through sequestration in alternative land-uses, such as afforestation (Byrne, 2010; O'Donnell et al., 2013) and re-wetting of peatlands (Bullock et al., 2012). While these additional land-use sequestrations may have important agricultural policy impacts via their contribution to national emissions reductions or re-prioritisation of current agricultural land, they are not direct indicators of agricultural sustainability, and have their own accounting methodologies within the greenhouse gas inventory (Duffy et al., 2017).

Incorporating extra data in the National Inventory Report and level of detail in emissions modelling

Ireland's international policy commitments on reducing greenhouse gas emissions are assessed through an annual National Inventory Report (NIR) submitted under the United Nations Framework Convention on Climate Change. This report uses verified and standardised methods to estimate the country's greenhouse gas emissions from all sectors. It is therefore important that any improvements to agricultural emissions intensity are recorded in ways that can update the NIR, as otherwise farmers' efforts to increase emissions efficiency will not be recognised. Policy commitments are set relative to emissions in a reference year (for example, Ireland must reduce its emissions by 30% by 2030, relative to 2005), and so improvements must be tracked over time to show continued uptake and progress and to justify reductions in emissions factors. Therefore, it is important that the established surveys described above continue to collect the relevant environmental data over time, and specialist surveys suggested above have the capacity for repeat surveys, depending on the need to establish baseline levels for specific technologies or management practices, and their anticipated uptake.

For other reporting schemes, the level of detail and collation of data depend on the objective. For example, the Bord Bia QA scheme is more focussed on international food marketing, and therefore estimates a complete life cycle carbon footprint for agricultural products, which includes emissions from energy use and farm imports not categorised as agricultural emissions in the NIR. The Teagasc NFS also collects sufficient data for life cycle assessment in dairy systems (O'Brien et al., 2015), with plans to increase the level of detail in other sectors. However, NFS reports to date use national

emission factors and accounting conventions in line with the NIR (Dillon et al., 2016; Lynch et al., 2016b; Dillon et al., 2017a). Both approaches are valuable. Life cycle assessment is important for international comparisons to demonstrate Ireland's emissions footprint per product and to assess the total impact of the agri-food industry. In addition, the greater range and detail of data collected can also form the basis of future developments and improve the NIR. In the meantime, applying the NIR IPCC approaches at farm level can provide insight into the apparent emissions efficiency of farms within the current policy framework, and relate this to wider farm management data. Relevant data to support the most detailed greenhouse gas methods should continue to be collected, but care must be taken when reporting results and describing accounting methodologies in order to be clear which emissions are being discussed (and particularly where the systems boundaries are drawn), and the implications for policy and environmental impact.

Pesticide Use

Regular pesticide usage surveys (approximately every four years per agricultural sector) are undertaken by the Department of Agriculture, Food and the Marine in compliance with EC regulation 1185/2009. In addition, the Bord Bia QA schemes include some survey questions on the use of pesticide safety measures and pesticide training. These data can provide a useful overview of relevant application details and a representation of national pesticide usage, which could potentially be linked with toxicity databases (Lewis et al., 2016). However, current data collection is not sufficiently detailed to generate pesticide risk assessments, which require integration of pesticide applications and site-specific biophysical conditions (e.g. Strassemeyer et al., 2017). It is difficult to recommend an ideal dataset to fully address pesticide risk due to the wide range and varying efficacy of pesticide risk indicators available (Pierlot et al., 2017). However, integration of pesticide usage with additional farm management data, either by extra detail in specific pesticide surveys, or by collecting further pesticide data (either directly or by linking surveys) on farms involved in wider sustainability assessment, could potentially contribute to an improved understanding of pesticide risk. Pesticide impacts on water quality are considered below.

Water Quality

Agricultural systems can result in significant loss of nutrients and/or pesticides to water, resulting in degradation of water quality. Water quality is one of the key environmental impacts of Irish agriculture (Wall et al., 2016). Water quality standards are established under three key policies: the Water Framework Directive (WFD, Directive 2000/600/EC), which sets baseline requirements for quality of water bodies; the Nitrates Directive (91/676/EEC) which requires states to implement Nitrates Action Programmes that set measures to limit agricultural nitrate pollution; and the European Union Drinking Water Directive (98/83/EC) which sets quality limits on water for human consumption. The WFD requires that all water bodies must be of good ecological and chemical status, and there must not be declines in the ecological or chemical quality status of any water body. 'Good status' is defined as only 'slight deviation' from water body conditions in the absence of anthropogenic pressures. Indicators of farm impact on water quality can take the form of either direct measurements of water quality in agricultural catchments, or farm-level mass-balance indicators of potential nutrient losses to water based on agricultural inputs and outputs and relevant management data.

Chemical water quality

In order to maintain water in good chemical water quality under the WFD, water bodies must be below legal thresholds, the Maximum Allowable Concentration – Environmental Quality Standard (MAC-EQS), for a list of specified compounds (most up to date list in Irish Statutory Instrument 386/2015).

In the most recent WFD assessment cycle (2012-2015) there was a single recorded incident of a pesticide (Isoproturon) MAC-EQS exceedance (Kieran Gordon, EPA, pers. comm.).

Under the Drinking Water Directive (most recently through Irish S.I. No. 122/2014), any individual pesticide concentrations must be below 0.1 µg per litre, and total pesticide concentration must be under 0.5 µg per litre. (Some pesticides have a limit of 0.03 µg per litre, but these are now banned in Ireland.) In recent years there have been incidences of pesticide detection above this threshold, particularly for the herbicide MCPA (4-Chloro-o-tolyloxyacetic acid, used to control rushes). More detailed pesticide risk indicators as described above, or additional pesticide use surveys for a compound of interest, could be useful to explore specific issues such as MCPA application and subsequent risks, carried out only on specific locations with a history or risk of pesticide exceedances.

Due the prominence of nitrogen and phosphorus losses in affecting ecological water quality through eutrophication (Mockler et al., 2017), indicators of these nutrient losses are considered below.

Ecological water quality

The Teagasc NFS generates farm management based indicators of risk to ecological water quality. Nitrogen and phosphorus balances are calculated for each farm by subtracting the nitrogen and phosphorus in agricultural outputs (e.g. crops, livestock and livestock products) from inputs (e.g. fertilisers, purchased feed and livestock), with the resulting surplus indicating a potential risk of environmental losses and subsequent water quality impacts (Buckley et al., 2015). The methodology is built on a range of farm management data, but there are a number of areas where nutrient fluxes are unknown, hence the potential to generate complete farm nutrient balances is limited. In particular, atmospheric deposition, manure and slurry transfers, biological nitrogen fixation and soil stocks represent potentially important nutrient imports for which reliable data are not currently available.

Mapping approaches demonstrate the possible scale of nitrogen (Henry and Aherne, 2014) and phosphorus (Johnson et al., 2017) atmospheric deposition across the country, which could eventually be incorporated as further nutrient inputs. As noted above for greenhouse gas emissions, the volume and nutrient content of imported manures and slurries is currently not well characterised. Biological nitrogen fixation, either through plant-associated or free-living microbes, may be supplying large quantities of nitrogen to Irish agricultural systems, even on top of high application rates of synthetic fertilisers (Enriquez-Hidalgo et al., 2016). A range of different assumptions have been used to estimate nitrogen fixation rates in European agriculture (Leip et al., 2011; Baddeley et al., 2013; Eurostat, 2013), which can have significant impacts on nitrogen input quantities (Godinot et al., 2016). Where relevant environmental and cropping information is known, nitrogen fixation can be modelled (Liu et al., 2011), but at present the presence and extent of clover or other nitrogen-fixing species in grasslands is not well described. Additional field surveys or linkage with other pasture management data would be required to include more accurate nitrogen inputs from biological fixation, either through site-specific models or more reliable standard values.

Mineralisation of soil nitrogen or phosphorus can translate into significant nitrogen inputs (Damon et al., 2014; Bünemann, 2015; Clivot et al., 2017), or conversely, immobilisation of soil nutrients may represent a loss to the system. Soil nutrient dynamics, similarly to carbon, are not currently well characterised for use in agricultural indicators, but the impact of soil nutrient availability and other chemical factors on nutrient loss pathways are becoming increasingly well understood (Mellander et al., 2016), with the potential for some details to be resolved through farm soil testing (McDonald et al., 2014). Development of nutrient balance indicators incorporating farm soil test results could be

useful in providing agronomic detail to inform best management practice, as well as more accurately indicating the risk of environmental losses. Soil surveys across a subset of representative or at-risk farms could prove a valuable addition in modelling these data. Alternatively, these data could be obtained from other sources, as many farms have recently adopted soil testing for their own management purposes or linked with relevant government schemes. The Teagasc online Nutrient Management Plan already collates soil test results and field-level management details, and the use of this database to model nutrient balances or provide additional data to other farm surveys could enable the development of more reliable indicators.

Moving from farm-level nutrient loss risk indicators to actual impact on water-bodies, and hence policy compliance with the Water Framework Directive, presents a further challenge in capturing enough site specific detail and modelling the relevant physical processes. The main interventions for agricultural management have been in setting nitrogen and phosphorus limits due to their significant impacts on water quality, but despite some evidence for the benefits of recent improvements in nutrient management (O'Dwyer et al., 2013), there is not always a clear relationship between agricultural nutrient inputs and impact on the catchment (Withers et al., 2014). Sediment loads are also recognised as a potential factor in declining water quality, but the mechanistic basis for these impacts is complex (Thompson et al., 2014), and limits are not currently established as part of agricultural policy.

There are a large number of other chemical contaminants with potentially significant effects on water quality which may not be explicitly targeted by policy actions (von der Ohe et al., 2011), but emerging analytic methods may drive further monitoring requirements and help resolve their impacts (Brack et al., 2016). Similarly, agricultural impacts on water quality through microbial pollution are recognised but require further research to build models appropriate to inform policy recommendations and develop appropriate indicators for evaluation (Oliver et al., 2016). Antimicrobial resistance is considered below in the context of the societal impacts of agriculture.

A recent systematic review of the effects of agriculture on water quality (Doody et al., 2015) highlighted the importance of incorporating spatial heterogeneity in order to model impacts, as well as the challenges resulting from the large number of factors influencing water quality simultaneously (including non-agricultural factors) and the potential delays between causes and effects (Doody et al., 2016). Integrating farm management data with relevant geospatial environmental data may present a means of overcoming some of these difficulties, in common with other topics described above.

Additional farm management mitigations relevant to water quality have been studied in Ireland, including riparian buffer zones (Ó hUallacháin, 2014), ploughing restrictions, soil testing and fertiliser limitations (Murphy et al., 2015), and remain an area of on-going research. Some relevant data are collected on these practices through the Teagasc NFS and Bord Bia QA schemes, but as with the impacts they are intended to minimise, their efficacy may be highly site-dependent, limiting their potential as indicators unless linked with the wider catchment environment and other factors affecting water quality (Page et al., 2012). Despite the additional complexity, this site-specific detail can aid in generating environmental indicators and guiding policy interventions, and there may also be economic benefits. Targeting of mitigations incorporating local geography could significantly reduce implementation costs (Thomas et al., 2016). Site-specific natural water retention measures, areas that retain water and can help support processes maintaining or improving water quality, such as wetlands or flood plains, can facilitate intensive agricultural production within a catchment, if the water retention features elsewhere sufficiently absorb the impacts (Doody et al., 2016). There are, however, significant knowledge gaps around the appropriate use of natural water retention measures to

counter agricultural impacts (Doody et al., 2016), and synergies or potential trade-offs with wider ecosystem services and objectives (Collentine and Futter, 2016).

The potential of natural water retention measures could be thought of similarly to off-setting agricultural greenhouse gas emissions by using agriculturally marginal land for sequestration. However, while off-setting of greenhouse gas emissions can be achieved at a national level due to the global nature of the impact, water quality must be maintained at catchment-scale. As noted above, re-wetting of some environments may confer additional benefits in greenhouse gas sequestration. Restoration of peatlands, for example, has been highlighted as offering potential improvements in water quality and climate change mitigation (Martin-Ortega et al., 2014).

The discussion above reflects a wider acknowledgement in the literature concerning the need for water quality indicators and mitigations to move from a simple 'pressure-impact' model to include the spatial and temporal detail necessary to understand the relevant processes (Doody et al., 2016). Farm-level mass balance indicators can still provide a relatively easy to generate indicator of potential risks to water, and can prove useful as a management tool to show what is achievable, while minimising nutrient losses and complying with the nitrates directive (Thomas et al. 2018). To generate direct water quality indicators and interventions reflecting policy requirements under the WFD however, will require on-going water quality research to incorporate site, time and goal-specific details.

Biodiversity

Several EU policies include the conservation of biodiversity as a policy goal, and it is also included in Foodwise 2025 (DAFM, 2015) as an environmental target for the agri-food industry. Although 'conservation of biodiversity' is often highlighted as a policy objective, biodiversity is a multi-faceted entity and it may be useful to consider a greater differentiation of farmland biodiversity. Such a differentiation could help guide the prioritisation and development of more specific objectives (as well as indicator selection and monitoring) for the broad spectrum of conservation values of species and habitats (which are not necessarily mutually exclusive) that may include: priority habitats/species on Natura 2000 (nature protection) sites; priority habitats/species that occur outside of Natura 2000 sites; rare and threatened species (e.g. those associated with Red Data Books, Species Action Plans, and legal protections); other species and habitats of high conservation value; farmland habitat to support species of high conservation value; and farmland habitats to support common farmland species (Finn and Ó hUallacháin, 2012). Similarly, the purpose of a monitoring programme or survey will have a strong influence on the sampling design and choice of indicators, which will vary greatly depending on whether the purpose is to assess the national state of biodiversity, the national state of biodiversity in agricultural areas only, the effects of specific policies, or whether minimum levels have been attained for the purposes of sustainability accreditation.

Generally (and not just in Ireland), the implementation of systematic, national monitoring programmes for biodiversity as part of sustainable agricultural practice lags behind that of other dimensions of agricultural and environmental sustainability. In Ireland, the National Biodiversity Action Plan, 2017-2021 (Department of Culture Heritage and the Gaeltacht, 2017), outlines a number of indicators for assessment of their biodiversity targets, including population monitoring for a number of species of high conservation priority. Given the prominence of agriculture as a land use in Ireland and the reliance of many wildlife habitats and species on specific types of agricultural management, biodiversity conservation is intimately tied to agriculture. The absence of a sufficiently detailed and high-resolution land use and land cover map for Ireland makes it difficult to assess the changing status of habitats at a national scale. More detailed remote sensing data can be used to supplement or replace this data collection on farm, and may enable reliable geospatial approaches for

generating biodiversity metrics in the future. It is likely, however, that these approaches will only be appropriate for assessing land use types (including semi-natural habitats) and changes in their distribution and extent, and will be insufficient to assess habitat quality for some time (although the technological capacity for doing this is developing rapidly). Nevertheless, improved information on the distribution and extent of habitat types would improve the ability to track change over time and space. One example is the Countryside Survey (www.countrysidesurvey.org.uk), which has been conducting national scale monitoring of a selection of 1 km grids in the UK countryside approximately every seven years since 1978 (Norton et al., 2012).

In Ireland, monitoring for habitats and species listed under the EU Directive on the Conservation of Habitats, Flora and Fauna (92/43/EEC) is regularly undertaken (every 6 years) and reported by the National Parks and Wildlife Service. This is one of the few Irish examples of a systematic, national-scale approach, and provides temporal and spatial trends for a number of threatened habitats and species in designated areas, many of which are associated with agriculture. A significant amount of farmland biodiversity in Ireland occurs outside of protected areas however (Matin et al. 2016; Walsh et al 2015), and there is growing recognition by policymakers of the need for conservation (and monitoring) of biodiversity in the wider countryside. Although there are numerous studies of farmland wildlife in specific geographical areas and in specific farming systems, there are very few monitoring studies outside of protected areas in Ireland that are systematically applied at a national scale.

Conservation in the wider countryside is exemplified by High Nature Value farming systems that are typically associated with high levels of semi-natural vegetation and farmland wildlife. High Nature Value farming systems are a headline environmental indicator for the Rural Development Programme of the CAP. Although they can overlap with the geographical distribution of protected areas, they are often not formally designated, but can still contain rare habitats and species (e.g. Walsh et al., 2015), and are typically a focus of agri-environment schemes. Tracking the extent, distribution, biodiversity, and targeting of financial supports (a policy aim) to high nature value farming systems implies a growing reliance on indicators for these attributes. In Ireland, length of linear habitats (hedgerows, etc.), stocking rate, and area of grassland under biodiversity-sensitive management had high predictive value as an indicator of high nature value for Irish pastoral farms (Boyle *et al.*, 2015). A GIS model based on similar criteria was developed to predict the national distribution of High Nature Value farming systems (Matin *et al.*, 2016). The use of predictive approaches based on land management practices can be a useful proxy for biodiversity, depending on the purpose. For example, information on land use can be used to generate an estimate of biodiversity potential. Kleijn et al. (2009) indicated an extremely strong relationship between plant richness and the amount of nitrogen fertiliser applied to grassland and arable areas. Similarly, many other studies have related farm management and structural indicators to farmland habitat diversity and selected groups of arthropods, mammals, birds, flowers and pollinators (e.g. Sybertz et al. 2017; Bredemeier et al. 2015).

National scale programmes can make an important contribution to monitoring biodiversity, but more demanding environmental objectives in areas of high environmental sensitivity require more targeted design and implementation of measures and thus, more targeted monitoring to assess whether biodiversity actions are achieving their intended policy aims. (Finn and Ó hUallacháin, 2012; Ó hUallacháin et al., 2016). Within the CAP and Rural Development Programme, agri-environment schemes are an especially important policy instrument for biodiversity conservation, but their effectiveness has been challenged, and the effects of measures are often inadequately assessed (e.g. Kleijn and Sutherland, 2003; European Court of Auditors, 2011). However, positive effects of agri-environment schemes also occur (e.g. Batáry et al 2015; Wood et al. 2015; Bright et al. 2015; Alison et al., 2017) and are usually associated with greater targeting. There has been growing interest in results-

oriented agri-environment schemes to include locally-targeted biodiversity indicators as part of the design and assessment process.

For example, in the Burren Programme (previously 'Burren LIFE' and 'Burren Farming for Conservation Programme' - the Burren is a karst landscape in the west of Ireland) farmers received funding depending on whether their management fulfilled habitat quantity and quality standards based on an assessment performed by farmers and advisors (McGurn and Moran, 2013). The scheme has widely been considered successful (Dunford, 2016) and the challenge is now to establish whether this approach could be rolled out across further regions and types of farm, ensuring that the habitat indicators used in such schemes are robust and demonstrably linked with the biodiversity outcomes they are intended to support.

Another example, the RBAPS project (Results Based Agri-environmental Payment Schemes, <https://rbaps.eu>) provided several case studies of the implementation of results-based payments for biodiversity provision in Ireland and Spain. Such schemes identify local objectives (typically in collaboration with local farmers and experts) as well as performance indicators that indicate the target environmental state. The closer the environmental state of the farm to the target state, the higher the payment. Such an approach explicitly uses indicators not just for an end-of-policy-cycle evaluation (summative assessment) but also to provide rapid and ongoing feedback to farmers on their distance to target (formative assessment) (e.g. see <https://rbaps.eu/scorecards>).

In recent decades environmental DNA (eDNA) techniques have extracted DNA from soil or other environmental sources in order to monitor biodiversity (Thomsen and Willerslev, 2015). This may provide cost-effective monitoring without field surveys based around individual species or taxa, and also expands the potential scope of indicators to include microbiological biodiversity that is currently not well characterised.

Embedded environmental impacts

Agricultural environmental assessments increasingly go beyond the immediate farm to include impacts incurred in the production of agricultural inputs. Although these are not associated with any immediate constraints in Irish agricultural policy, full environmental assessments are an important consideration in the promotion of Irish food and the continued growth of international exports. For example, the current carbon footprinting certification schemes are based on lifecycle assessments including energy-use based emissions in the production of synthetic fertilisers, and agricultural and land-use emissions in the production of off-farm feeds. Similarly, while direct agricultural water use is not a major consideration for Irish agriculture (Murphy et al., 2017), virtual water flows describing water use embedded in inputs also receive significant attention (Hoekstra and Mekonnen, 2012).

There is also growing recognition of the potential magnitude of off-farm impacts of agricultural systems on the biodiversity of geographically distant areas. This impact is not represented by measures of wildlife species or habitats that are limited to the boundary of an individual farm (Teillard et al. 2016, Wilting et al., 2017). Life Cycle Assessment methods are being developed to better quantify multiple impacts of agricultural products on biodiversity through models that associate different land use classes with different levels of biodiversity (e.g. de Baan et al., 2013; Chaudhary et al. 2015). Failure to incorporate such off-farm effects can seriously underestimate the aggregated effects on biodiversity, and can confound decision-making that seeks to minimise the impacts. For example, the conversion of natural habitats in biodiversity hotspots to arable areas for the production of protein crops for animal feed represents a globally significant off-farm biodiversity impact.

Data on imported agricultural inputs collected in the Teagasc NFS and Bord Bia QA schemes in order to carry out greenhouse gas life cycle assessment can be used for these further embedded impacts as standardised methodologies are put into practice. Further detail on the source of these inputs, for example the place of manufacture of fertilisers, would allow more accurate embedded impact assessment, as there are country-specific assumptions about the impacts of production and transport of different products. Identifying the geographical origin of off-farm feed can be challenging when globally traded commodities are involved, but potential indicators include trends in the usage of off-farm feed, locally-sourced feed and feed that is accredited as being 'responsibly sourced'.

Economic sustainability

The economic sustainability of agriculture, both at individual farm and sectoral scales, is an important objective of the Common Agricultural Policy (CAP), and the topic currently receives particular attention in Ireland due to the potential consequences of the impending United Kingdom withdrawal from the European Union. Farm-level economic sustainability indicators, describing, for example, profitability, productivity and viability, can be used to identify which systems are succeeding or struggling. Over time these indicators can be used to assess whether the situation has improved or worsened (for specific farm-types or the sector as a whole), and at an aggregated level can suggest how agricultural economic sustainability responds to policy or wider trends. Comparisons across different indicator categories can also provide insight into potential economic costs or benefits of responding to other sustainability challenges.

A number of indicators of farm economic performance, including farm viability (Lynch et al., 2016b) and competitiveness (Thorne et al., 2017), have been generated through routinely collected Teagasc NFS data. The Teagasc NFS Small Farms Survey supplements these data with a sample of farms of a lower food output value (Dillon et al., 2017a). Overall, the economic data collected as part of these two surveys, supplemented with national and international output and trade statistics, have been successfully used to explore a range of relevant policy concerns relating to economic sustainability. Recording off-farm income is potentially important in order to estimate viability, as loss-making farm businesses may be sustained through off-farm employment (Hennessy et al., 2008), but due to sensitivities around collecting these data within farm finance surveys it is unlikely to be collected as part of current European recording schemes (O'Donoghue et al., 2016). The Teagasc NFS records the off-farm income of farm owners in incremental income bands of approximately €5,000, which could be used for some illustrative purposes, but as a result of the sensitivity around this topic these data are not currently used in economic analysis as the primary purpose of the survey is to examine the on-farm component of income.

One further area relating to economic sustainability currently receiving particular attention in Ireland is how so-called 'own labour' (unpaid labour provided by the farm operator and in some cases other family members) is taken into account in economic metrics. The Teagasc NFS follows standard FADN conventions in not including own labour as a production cost, as the farm income represents the farmer's return on their farm labour, management input and capital, from which it is difficult to segregate individual components. However, some have argued that it would be useful to have own labour inputs expressed as a specific cost and included in enterprise gross margins, and particularly in the context of increasing labour demands for the expanding dairy sector (Kelly et al., 2017). A recent dairy enterprise overview has attempted to address this by including a value of own labour based on self-reported labour input, defined in hours (Dillon et al., 2017b). Though the exercise was useful in establishing an estimate of the volume of own labour, and highlighted the range in that volume between farms based on, for example, herd size and facilities structure, there were also difficulties in reliably estimating the value of that labour, which is typically priced on the basis of opportunity costs.

Further studies could generate more reliable labour costs by more accurately measuring hours worked through, for instance, more frequent and detailed surveys recording hours worked, or through activity-measuring smartphone applications (Bort-Roig et al., 2014).

Volatility in both input and output prices poses a real challenge to the economic sustainability of farms and underlines the importance of utilising risk management strategies to deal with income volatility where possible. One such stabilisation mechanism is that of forward contracting, which is relatively common in the cereals sector where the perception of price volatility is high. Similarly, fixed price milk schemes are designed to assist dairy farmers in the management of milk price volatility, guaranteeing a secure price on a fixed proportion of supply. According to Helaine and Uboldi (2017) the volumes traded in dairy futures markets in the EU are low but increasing, whereas forward contract arrangements and other forms of (publicly subsidised) insurance are more commonplace in the United States (Burdine et al., 2014; Wolf and Widmar, 2014). In an Irish context, such arrangements are likely to become more common given the increased market risk inherent in a post milk quota era. In protecting against potential income volatility in this way, planning around investment and expansion can also be put in place. Research by Loughrey et al. (2015) using Teagasc NFS data found that farm diversification, demographic variables, milk quality and the farmer's individual milk price history are significantly associated with the likelihood of adoption of forward contracts. The expansion of the Irish dairy sector to date has primarily been through increased productivity and efficiency, with further growth likely to be more reliant on increased land area and debt acquirement. At present, a shortage of skilled hired labour on expanding farms also poses a real challenge. All of these issues should be borne in mind in on-going sustainability assessments.

Social sustainability

Social wellbeing is an important component in assessing the impacts of the CAP, both in relation to individual farm support, and its role in the entire agricultural industry. It is important that working in agriculture provides an acceptable quality of life (in addition to an acceptable income), that the 'second pillar' targets of rural development are also met through relevant agricultural support payments, and that agricultural activity is of value to society.

The multi-dimensional aspects of sustainability are widely accepted, however, the measurement of social sustainability has been least widely adopted thus far. As the concept continues to develop, diverse issues such as wellbeing, quality of life, resilience and demographic change are all worthy of investigation, not least in the context of policy design and evaluation. Similarly, issues relating to farm and food safety and animal welfare as well as social capital and integration are all of relevance.

Farm scale social sustainability

The Teagasc NFS produces a number of farm-level social indicators derived from its annual data collection (Dillon et al., 2016; Lynch et al., 2016b). In 2015, a number of further social welfare questions were also asked as part of an EU project (FLINT, Poppe et al., 2016). The FLINT project explored additional FADN data collection, including farmer assessments of their personal quality of life and job satisfaction, and details relating to labour such as holidays and free days taken, cover in case of illness, the number of hours worked off-farm by the farmer or their spouse, and farmer attendance of social events (Herrera et al., 2016). Further social sustainability questions were also posed in the recent Teagasc NFS Small Farms Survey (Dillon et al., 2017a), covering the level of contact farmers have with others, the sense of security they feel in their community, and their ability to access local services such as a Garda (police) station, post office or public transport. These additional

questions have proved valuable in providing information on farm social sustainability, and are currently being considered for inclusion in future surveys on a regular or occasional basis.

Farm succession and inheritance is also an important social sustainability issue in Irish agriculture, due to the relatively high age profile of Irish farmers (average age of 56 in 2016, Dillon et al., 2017c) and long-term emigration from some farming areas (O'Rourke et al., 2012). Some of the questions included in Teagasc NFS surveys described above have provided insight into these topics, for example household demographics in the regular reporting and farmers plans for the future in the small farms survey. Recent research has also highlighted the importance of social, cultural and symbolic capital in explaining farmer attitudes to succession, and has been explored with surveys on, for example, farmers' plans for retirement, and illustrated responses with qualitative interviews shedding light on farmer's opinions and behaviours (Conway et al., 2016). Similar surveys could be repeated on an infrequent basis, or these issues could be further investigated in sectors deemed most at risk.

The subjective and broad nature of social sustainability does not easily lend itself to measurement by quantitative analysis of specific farm activities, as opposed to environmental or economic sustainability. Instead, analysis of the social aspects of sustainable development also requires a community focused qualitative measurement approach. To this end, efforts are on-going to further refine the existing metrics of social sustainability within the Teagasc NFS.

Societal concerns: new frontiers for sustainability assessment

Social sustainability beyond the farm and immediate community reflects whether agricultural outputs are of net benefit, and if the means of producing them are acceptable to society.

Animal welfare is an increasingly important topic for consumers and has on-going support in EU legislation, most recently in the formation of an expert group 'platform on animal welfare'. Minimum requirements for animal welfare are established under EU and Irish law, with some higher welfare demands as part of Quality Assurance schemes. Other data on animal welfare have come through additional survey exploring aspects such as livestock mortality rates (Mee et al., 2014). Recent technologies can enable very detailed collection of animal welfare data through, for example, automated audio and visual analysis of livestock (Berckmans, 2014) and wearable (Neethirajan, 2017) or internal (Warren et al., 2008) monitoring devices. Surveys could employ these techniques to study specific animal health and welfare concerns, or use data collected from these methods if farmers implement them independently or, for example, as part of future QA schemes.

The use of antibiotics in agriculture, and the potential for development of widespread antimicrobial resistance is an important topic (Hudson et al., 2017), and has received much attention from wider society (Morris et al., 2016). At present, indicators of farm antimicrobial use are limited to national statistics on antibiotic use per animal as reported by the EU (European Medicines Agency, 2016), and the per farm expenditure on veterinary services and medicines as recorded in the Teagasc NFS. More detailed questions on specific antibiotics and their use could potentially be added to surveys where there are specific concerns. Recent technologies such as antimicrobial resistance gene detection chips or large scale sequencing could also be employed on farms or in the wider environment to identify where there is resistance and better understand the risk posed (Thanner et al., 2016).

The presence of genetically modified (GM) material in the agri-food chain is of on-going importance to consumers and wider society, and demand for non-GM produce in export markets makes it an important food policy consideration (Fox, 2017). Under present legislation, there is complete segregation of GM and non-GM food production within the EU, but there is not always clarity in the composition of feeds imported from outside the EU, and whether they contain GM ingredients (Kleter

et al., 2017). Further detail and traceability of imported animal feeds could enable better tracking of GM feedstuffs, while also contributing to more detailed estimation of embedded emissions and other environmental impacts, as described above. Screening technologies such as ddPCR (Droplet Digital PCR) could also be employed to identify GM components of feedstuffs with a high degree of sensitivity (Morisset et al., 2013).

Farm data confidentiality

The ability to generate detailed and reliable indicators of agricultural sustainability has been greatly enhanced over recent years as a result of increased collection and sharing of agricultural data (Zaks and Kucharik, 2011). Cooperation between industry and state actors and integration of relevant databases held by each, such as the Department of Agriculture, Food and the Marine Animal Identification and Movement System (AIMS) and the Teagasc NFS can lighten the burden on farmers by minimising repeat data collection and enhance the accuracy of indicators by expanding the range of relevant data available for analyses. Remote sensing technologies enable further detail to be combined through, for example, geospatial integration of individual farms with satellite data, while the growth in on-farm monitoring technologies to aid farm management could provide further relevant data, if farmers are agree to data-sharing. Despite this potential, these developments also present a number of significant challenges (Wolfert et al., 2017), including issues relating to data protection and confidentiality. Unless data acquisition and use is sufficiently transparent, yet also able to maintain individual farm confidentiality where appropriate, there may be a loss of faith by farmers resulting in refusal for data to be shared, and ultimately a reduction in the ability to generate robust sustainability indicators. In the European Union, including Ireland, agricultural data collecting agencies must be compliant with the General Data Protection Regulation (EU regulation 2016/679), which came into force in May 2018.

Conclusions

There is significant scope to continue developing existing and further expand the range of Irish agri-food sustainability indicators, across a number of important topics. Developing an integrated set of metrics linking environmental, economic and social sustainability might appear onerous for those focused only on one strand of sustainability. However, a holistic, multi-disciplinary collaboration can allow integrated data collection and identify synergies or trade-offs in the provision of desirable outcomes, reflecting the multi-dimensional impacts and outputs of agricultural activity. Therefore, in the course of the identification and development of individual indicator topics, consideration should be given to whether such research can become part of a wider sustainability indicator development and assessment programme.

In the case of environmental indicators, these developments are a result of on-going policy issues and the volume of recent scientific research published on the topics in question. As our scientific understanding of the environmental impacts of agriculture matures, the complexity and level of detail desirable for generating sustainability indicators has also increased. While this presents some challenges in data collection and modelling capacity, many data needs can be met through emerging technologies (e.g. remote sensing) and continued integration of agricultural databases, and additional data requirements frequently overlap for multiple indicators.

For economic and social sustainability, the current indicators are able to explore many relevant policy issues, and potential developments are driven by emerging topics. Some of the indicator developments described above can be readily integrated into existing national data collection and indicator schemes, while others may reflect one-off or occasional studies required to evaluate specific

policy needs. While there is a need to consider the trade-off between the benefits of greater data collection and coverage against the risk of surveys becoming too invasive or time-consuming, we should strive to develop our agricultural indicators to gain a more reliable measure of the wider impacts of agricultural systems. Interrogation and continued development of agricultural indicators, as discussed above, can contribute to a wide range of policy topics to ensure humanity's agricultural needs are met in a sustainable manner.

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1082 Table 1. A selection of the main Irish organisations and programmes connected to agri-food sustainability

Organisation / Programme	Description
Teagasc, the Irish Agriculture and Food Development Authority	An Irish semi-state body with responsibilities in agriculture and food research, extension and education.
Teagasc National Farm Survey (NFS)	Annual survey of approximately 1,000 farms, providing Ireland’s submission to the EC Farm Accountancy Data Network (FADN). Primarily focussed on economic data but more recently expanded to include environmental and social sustainability indicators.
Bord Bia	Irish state agency responsible for assurance schemes and national and international promotion of Irish food.
Origin Green	Voluntary food and drink sustainability programme led by Bord Bia covering the supply chain from production to retail
Sustainable Dairy Assurance Scheme (SDAS)	Dairy farm quality assurance scheme rolled out in 2014. Operated by Bord Bia, it was the first component of the Origin Green programme. Now joined by Sustainable Beef and Lamb and Sustainable Egg Quality Assurance Schemes, with programmes in development for other sectors.
Environmental Protection Agency (EPA)	Independent public body with responsibilities in environmental monitoring and regulation. Key roles associated with Irish agriculture include compiling and reporting national greenhouse gas emissions, monitoring for and enforcement of water quality legislation, and pesticide use surveys.
Department of Agriculture Food and the Marine (DAFM)	Department of the Government of Ireland responsible for monitoring and control of food safety, animal health and welfare, and development and implementation of national and European agricultural regulation and policy.

Table 2. Overview of the major Irish agri-food sustainability indicators and potential developments addressed in this review

Indicator topic	Current indicators / programmes	Potential for improvement	Challenges to implementation
Environmental			
Greenhouse gas emissions	Product and farm level emissions estimates/relevant data from Teagasc NFS and Bord Bia QA schemes	Expand number and type of farms covered	Increased survey scale
	Total emissions in National Inventory Report	Integrate with wider secondary datasets Integrate more farm-level activity data collected in other programmes Incorporate new research to update Irish emission factors	Data harmonisation and permissions Data harmonisation and permissions Research undertaking, potential increase in extent and detail of farm surveys required for activity data
Pesticide Use	Pesticide Usage Surveys (for EC reg. 1185/2009)	Risk indicator of pesticide use	No single widely adopted approach, potential increased survey demand
Water quality	Farm nutrient balances	Improve detail in nutrient balance methodologies	Lack of data and scientific underpinning of some elements (e.g. biological nitrogen fixation, soil stocks)
	Monitoring for ecological and chemical water quality (as part of WFD)	Link farm nutrient balances with additional models and secondary data to predict actual impacts	Complex modelling required with significant data demands and need to operate at catchment level (incl. multiple farms and non-agricultural sources)
Biodiversity	Specific agri-environment schemes including relevant habitat assessments (e.g. Burren Programme)	Design and implement similar schemes for a wider range of locations and farm types	Further schemes require appropriate, context specific design
	Monitoring for EU Directive on the Conservation of Habitats, Flora and Fauna priorities	More regular and widespread monitoring to occur outside of protected areas	Significant survey requirement
		Land-use mapping to track habitat types	Research and survey effort in identifying and conforming beneficial habitats
Economic			
Farm Economics	Farm profitability Farm viability	Standardise and improve measurement of farm labour Potential role of off-farm income	Sensitive and difficult to survey Sensitive survey topic
Social – farm-level			
Farming wellbeing	Farming demographics Rural quality of life	Qualitative approaches on e.g. farm succession plans Expand number and type of farms covered	Sensitive and difficult to survey Increased survey scale
Social – societal concerns			
Antimicrobial resistance	National / per animal sales of antimicrobial agents	On-farm monitoring of environmental loads and risks of resistance evolution	Detailed survey required
Animal health and welfare	Spending on medicines and veterinary services	Metrics based on novel monitoring techniques for animal health and productivity	Potential survey requirement and data permissions
Genetically modified foodstuffs	Separation of production within Europe under EU legislation	Tests for GM content in imported feedstuffs and track over full supply chain	Additional testing required, may be complicated by mixed-source feeds