Research Article • DOI: 10.1515/ijafr-2016-0011 IJAFR • 55(2) • 2016 • 112-125

Irish Journal of Agricultural and Food Research

Developing farm-level sustainability indicators for Ireland using the Teagasc National Farm Survey

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Abstract

In the context of an expanding, export-dependent agri-food sector, indicators of sustainable development and intensification are necessary to measure, assess and verify the comparative advantage afforded by Ireland's natural pastoral-based food production systems. Such indicators are also necessary to ensure that we produce more food with less adverse impacts on the Irish environment, climate and society. This article outlines the development of farm-level indicators that reflect the multifaceted nature of sustainability, which is encompassed in economic, environmental and social indicators. The role of innovation in farm sustainability was also examined. A comparison of indicators across Irish farm systems showed that dairy farms, followed by tillage farms, tended to be the most economically and socially sustainable farm systems. In relation to greenhouse gas emissions in particular, the top-performing dairy farms, in an economic sense, also tended to be the best-performing farms from an environmental sustainability perspective. This trend was also evident in relation to the adoption of innovative practices on farm, which was found to be strongly correlated with economic performance.

Keywords

agriculture • farm survey data • sustainability indicators

Introduction

The "Grand Challenges" for food and agriculture in the 21st century include population growth, climate change, energy and water supply, all of which affect the potential of agriculture to provide an increasing secure supply of safe food ([FAO], 2009). As a result, the "sustainable intensification" (SI) of agricultural production has become a priority issue for policymakers and international development agencies (Herrero and Thornton, 2013). A recent conceptualisation of SI undertaken by a large group of scholars identifies the following four underlying premises: (i) the need to increase production, (ii) the need to meet increased food demands from existing agricultural land, because opening up new land for agriculture carries major environmental costs, (iii) the need for food security concerns to be taken into account in increasing food production and (iv) the need for new approaches to be tested within biophysical and social contexts (Garnett *et al*., 2013).

In recent years, there has been a concerted effort to monitor progress towards SI (e.g. Frater and Franks, 2013; Barnes and Thomson, 2014). In Ireland, the industry-developed strategies for the agri-food sector – Food Harvest 2020 (DAFF, 2010) and Food Wise (DAFM, 2015) – set ambitious agricultural expansion targets for the dairy sector in particular (Dillon *et al*., 2015). Many approaches to accomplishing the dual challenge of increasing agricultural production while reducing its environmental impact are based on increasing the efficiency of agricultural production relative to both resource use and the unintended outcomes of use such as water pollution, biodiversity loss and greenhouse gas (GHG) emissions (Bennett *et al*., 2014). This calls for a new category of indicators that measure the efficiency of agricultural production in relation to both inputs and environmental impact. Innovation in agriculture also has a key role to play in producing more food without depleting natural resources (World Bank, 2007). Innovation is a broad concept but it is fundamentally about embracing novelty. Thus, indicators of innovation can be used to gauge what farmers may be doing today but will affect their future sustainability (OECD and Eurostat 2005).

The breadth and depth of data collected at the farm level (particularly relating to the environment) in Ireland have expanded considerably in recent years, allowing for the development of a broad suite of indicators. The objective of this article is to describe the development of a proof of concept in relation to a number of economic, social and environmental sustainability indicators, building on work initiated by Dillon *et al*. (2007, 2010), by broadening and deepening the range of indicators developed. We describe the sustainability criteria to be measured and the variables used to develop the relevant indicators. Additionally, we describe the development of indicators to reflect production efficiencies and indicators of innovation based on the adoption of new or innovative farm practices. These indicators are examined

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for the main Irish farming systems, namely dairy, cattle, sheep and tillage, and these are then aggregated nationally to facilitate more detailed analysis and discussion of the results.

Theoretical context

For SI to be effective, it will involve more than marginal improvements in sustainability – "successful SI will involve taking the multi-functional objectives of agriculture into account" (Campbell *et al*., 2014). The goal of the European Union (EU) Bioeconomy Strategy – "Innovating for Sustainable Growth" – is to move to a more innovative and low-emissions economy, reconciling demands for sustainable agriculture and food security while ensuring biodiversity and environmental protection (EC, 2012). This increased complexity demands a more systematic examination of how sustainability is measured and highlights the need to develop methodologies to quantify the SI of food production. Collaborative initiatives such as the Department for Environment, Food and Rural Affairs (Defra)-funded Sustainable Intensification (Research) Platform (SIP, 2015) in the UK and the EU-funded project Farm Level Indicators for New policy Topics (FLINT) bring a wide range of scientific, economic and social researchers together to develop internationally comparable sustainability indicators. Indicators should be scientifically valid, analytically sound, measurable and verifiable and, as such, depend hugely on the availability of robust data, which are updated at regular intervals (FAO, 2003). Where time series data are available to illustrate trends over time, they can provide an early warning of potential future economic, social or environmental damage.

In comparison with intensive agriculture in other countries, Irish farming is not particularly intensive in nature. However, in 2012, more than 30% of Ireland's GHG emissions came from the agriculture sector (EPA 2013), whereas the corresponding average for the EU was just over 10% (Donnellan, 2014). As a result of the high share of ruminants (dairy and beef animals) in Irish agriculture, ruminant agriculture is more emissions intensive than other forms of agriculture. These emissions consist of methane (CH_4) – which is generated as a by-product of the natural ruminant digestive process (enteric fermentation) – and nitrous oxide (N_2O), which is generated from both animal waste and use of N fertilisers (Donnellan, 2014). The dominance of beef and dairy production in Ireland accounts for the high proportion of agricultural GHG emissions in Ireland (Breen *et al*., 2010). However, on aper– kilogram-of-product basis, GHG emissions generated as a result of agricultural production in Ireland are among the lowest internationally. A study by the EC has shown that Irish agriculture has the lowest carbon footprint in the EU for milk and the fifth lowest carbon footprint in the EU for beef (Leip *et al*., 2010).

There is a growing awareness of the need to further develop existing market opportunities and exploit new international food market opportunities in a sustainable way that minimises the impact on land use and GHG emissions. Consumers in all markets demand enjoyable, safe, healthy and high-quality food products (Trienekens *et al*., 2012). In Ireland, the ambitious agri-food sector expansion targets (DAFF, 2010; DAFM, 2015) highlight the importance of the measurement of the relative sustainability of agriculture and food exports. This provides the sustainability credentials for the "Origin Green" export marketing campaign, which gives Irish food exports a comparative advantage. Ireland's food marketing board (Bord Bia) has built its Origin Green marketing campaign on the extensive, low-input, grass-based production systems used in Irish food production.

Trends in meat consumption suggest that the influence of factors such as income and price will decline over time and that other factors such as quality will become more significant in influencing consumer choice (Henchion *et al*., 2014). Additionally, large retail outlets are also increasingly demanding that their food suppliers adhere to the principles of sustainability and traceability, while consumers are willing to pay a premium for sustainably produced food (Government of Ireland, 2012). The term "credence attributes" refers to health and process benefits that may satisfy moral and ethical needs, despite the inability of individual consumers to assess/confirm their existence (Henchion *et al*., 2014). However, Verbeke *et al*. (2010) note the significance of confidence, trust and the value placed on certification by independent institutions.

Indicators of innovation are becoming more important (Diazabakana *et al*., 2014) as sustainability is not static by nature. There is a growing literature that suggests that the level of innovation is an indication of the long-term sustainability or resilience of farms (Leeuwis, 2004; World Bank, 2007; Renwick *et al*., 2014). According to Johnson (2010), innovations arise through the "coming together of ideas and practices" and through experiments as "there can be no innovation without failures". Thus, fostering communication and networking is important to enable learning from experiments and to transmit innovation (World Bank, 2007). The development of sustainability indicators also allows researchers to benchmark the multifunctional aspects of agricultural sustainability and informs innovative knowledge transfer initiatives for farmers such as the Teagasc Carbon Navigator (Murphy *et al*., 2013). In order to remain competitive, farmers need to innovate continuously, so as to adapt to market developments and changes in resource quality and availability. As market pressures change over time (e.g. price volatility, cost price squeezes, environmental pressures and demographic changes), innovations are required to maintain the status quo in terms of reaching sustainability objectives (UN, 2013). To encourage agriculture that is both resilient and sustainable, approaches to agricultural development that encourage experimentation, innovation and learning are needed (Bennett *et al*., 2014).

Data and methodology

This paper presents the development of farm-level sustainability indicators across economic, environmental, social and innovation dimensions, based on an earlier report published by Hennessy *et al*. (2013b). Indicators were chosen according to their overall suitability in an Irish socioeconomic context and were developed using Teagasc National Farm Survey (NFS) data from 2012. The NFS has collected farm-level data annually since 1972, in order to report to the EU Farm Accountancy Data Network (FADN), which provides a harmonised platform for the collection of farm statistics across Europe. The NFS is composed of a random, nationally representative sample of ~1,000 farms annually. Each farm is assigned a weighting factor so that the results of the survey are representative of the national population of farms in Ireland. Each farm is assigned to one of six different farm systems on the basis of the composition of the farm's gross output, as calculated on a standard output basis. Standard output measures are applied to each animal and crop output on the farm, and only farms with a standard output of €8,000 or more are included in the sample (Hennessy *et al*., 2013a).

Economic indicators

Although much of the focus in the sustainability debate is directed towards environmental resource management, farms must also be economically viable to be sustainable in the longer term. Farm-level measures of sustainability that capture the broad concepts of productivity, profitability and viability are presented in Table 1. The return to labour invested on the farm is measured as family farm income (FFI) per unpaid labour unit employed on the farm. FFI includes a deduction for hired labour, and hence the measure only includes unpaid family labour and does not include a payment for family labour. An economically viable farm is defined as having the capacity to remunerate family labour on the farm at the average agricultural wage and the capacity to provide an additional 5% return on non-land assets (Frawley and Commins, 2000).

Environmental indicators

The nature of the interactions between agricultural practices and the environment is complex with consequent difficulties in developing meaningful environmental indicators. However as scientific knowledge of these interactions increases, there will be greater clarity on the extent and nature of the data required for the future development of indicators. The environmental thematic areas that are of most concern in Ireland include air quality, climate change, risk to water quality and biodiversity (EPA, 2013). The collection of environmental data in the NFS is relatively recent, but sufficient data exist to develop indicators of air and risk to water quality. However, the NFS does not collect farm-level biodiversity data; thus, the development of biodiversity indicators poses particular challenges (Hennessy *et al*., 2013b), which are not addressed in this paper.

Air quality

Agriculture in Ireland accounted for a third of total GHG emissions in 2014 (EPA, 2015). The process of measurement, reporting and verification of GHG emissions from the agricultural sector is complex from both the scientific and administrative perspectives and, as a result, the methodologies selected to measure GHG emissions are often dictated by the availability of environmental data. Sufficient activity data are available within the NFS dataset to estimate GHG emissions associated with each farm enterprise using the Intergovernmental Panel on Climate Change (IPCC) coefficients, conventions and nationally appropriate emission factors to produce an estimate of total emissions per farm.
The methodology utilises a combination of Tier 1 and Tier 2 approaches to estimate GHG emissions per farm (tonnes of carbon dioxide equivalent (tCO_2eq) by applying relevant IPCC coefficients to animal numbers (on the basis of age category). IPCC Tier 1 utilises simple methods with default values. Tier 2 methods include country-specific emission factors. Tier 3 includes more complex approaches, possibly models. Production efficiencies are taken into account by measuring GHG emissions (CO_2eq) per kilogram of product produced for the main products generated by the dairy, cattle

Table 1. Economic measures

Indicator	Measure	Unit
Productivity of labour	Income per unpaid labour unit	€/labour unit
Productivity of land	Gross output per hectare	€/ha
Profitability	Market-based gross margin (less subsidies) per hectare	€/ha
Market orientation	Proportion of output derived from the market	%
Farm viability	Farm is economically viable	1 = viable, 0 = not viable

and sheep systems. In the case of dairy farms, this is possible using NFS data as physical volumes of milk (in kilograms) are recorded. However, it is more challenging to develop per unit product indicators for tillage farms as further work is required to allocate emissions to the particular tillage crops cultivated on the farm. For cattle and sheep farms, it is necessary to estimate kilograms of output by estimating animal live weight produced from animal sale values.

The air quality measures examined here are confined to GHG emissions occurring inside the farm gate and quantify emissions using a national sector-based approach. The more holistic life cycle analysis approach that measures emissions along the length of the food chain, from the production of agricultural inputs right through to the retailer and consumer, is more data demanding and is beyond the scope of this analysis.

Emissions from fuel and electricity used on the farm and by hired contractors also contribute to overall agricultural emissions. These emissions are estimated separately from the above indicators and are presented for the dairy, cattle and sheep systems in relation to the volume of output produced.

Risk to water quality

Nitrogen (N) is one of the main elements underpinning agricultural production. However, surplus N can pose a risk to the aquatic environment depending on the local biophysical landscape. Optimal use of N can deliver the double dividend of reduced risk of nutrient loss from agricultural land while increasing income at the farm level (Buckley *et al*., 2015). The links between N balance (imports of N less exports) at the farm and field levels and N loss to the environment are complex and difficult to predict as the nature of the interactions depends on a myriad of factors such as soil type, hydrology, weather, farm structures and management practices (Jordan *et al*., 2012). However, approaches such as farm-gate- and whole–farm-level nutrient balance accounting provide a reliable assessment of nutrient management efficiency at the farm or enterprise level while also providing an indicator of environmental pressure in relation to risk to water quality. The farm gate approach restricts analysis to imports and exports of nutrients over which the farmer has direct control (through the farm gate). Ideally, holistic whole farm soil/surface indicators would take account of the nutrient status of the soils, but the full range of data required to undertake a whole farm balance analysis is not available within the NFS.

Utilising the available NFS data, a farm gate measure of the risk to water quality was developed for all systems. This indicator was calculated as total quantities of N imported less total quantities of N exported, on a per-hectare basis. Each of the products exported from the farm (e.g. milk, meat, tillage and wool) and the imports (mainly chemical fertilisers and feedstuffs) are converted to kilograms of N using relevant coefficients (Buckley *et al*., 2015, 2016). Table 2 presents the air quality and risk-to-water measures examined in this paper.

Social indicators

The social contributions of agriculture in rural areas, which include, inter alia, sustaining the economy, services and infrastructure relied upon by rural populations, as well as providing a repository of skills and knowledge, which helps to keep alive rural cultures and traditions, are highlighted by Cooper *et al*. (2009). Agriculture is also relevant to the quality of life in rural areas in terms of its economic and environmental contributions (e.g. creation of landscape and reduction of pollution). Social sustainability, as defined by Lebacq *et al*. (2013), relates to the well-being of farmers and their families, in relation to (i) education; (ii) working conditions, measured by working time, workload (including health) and workforce; and (iii) quality of life, measured by isolation and social involvement. There is a growing recognition of the need to examine overall human well-being and quality of life within the sustainability framework (Elkington, 1999; McKenzie, 2004; Littig and Griessler, 2005; Pilgeram, 2011). Welfare issues such as access to education, working conditions, risk of social isolation and lack of young people on farms, all affect the well-being of farm families.

The social sustainability measures presented in Table 3 and described here, quantify issues that affect quality of life at the farm level, rather than at the societal level. A household is defined as vulnerable if the farm is not economically viable, where an economically viable farm has (i) the capacity to remunerate family labour at the average agricultural wage and (ii) the capacity to provide an additional 5% return on non-land assets (Frawley and Commins, 2000), and if neither

Table 2. Environmental measures

Indicator	Measure	Unit
GHG emissions per farm	IPCC estimate/farm	t CO_2eq/farm
GHG emissions per kilogram of output	IPCC estimate/kg of output	CO_2eq/kg output
Nitrogen (N) balance	Risk to water quality	kg N surplus/ha
Emissions from fuel and electricity	CO_2eq/kg output	CO_2eq/kg output

GHG = greenhouse gas; IPCC = Intergovernmental Panel on Climate Change.

the farmer nor the farmer's spouse is employed off-farm. The education level of the farm household members is used as an indicator of the makeup of the household in the context of farm succession. Households are classified as being at risk of isolation if the farmer lives alone. An examination of the age profile of farm households can be indicative of demographic viability, and farm households are designated as being of high age profile if the farmer is aged older than 60 yr and there is no household member younger than 45 yr. Finally, work–life balance is calculated by taking account of the hours worked by the farmer on the farm.

Indicators of innovation

At the farm level, many innovations are process innovations. They relate to the adoption of new production techniques, e.g. the use of improved seeds or the adoption of management practices that optimise resource efficiency (land, animals, nutrients, human capital and technology), thereby reducing impacts on the environment, but also reducing production costs. By contrast, organisational innovations include the adoption of farm partnerships and share farming.

Research and business provide inputs into farm-level innovation, but actual innovation only occurs when farmers put something new into use. The uptake of innovation by individuals is referred to by Leeuwis (2004) as "adoption" of innovation. Farm extension advisers can facilitate the adoption and diffusion of innovation among farmers in order to improve production efficiencies and overall sustainability. In relation to the Irish agri-food sector, Renwick *et al*. (2014) found that the strongest barriers to innovation exist at the farm level and recommended a move from scheme-driven to innovation-driven advisory services. In this context, NFS data on the adoption of new technologies or participation in knowledge transfer programmes were used to develop measures of farm innovation. As innovations are generally specific to the farm system, innovation indicators that are appropriate to each system were developed in this study.

The dairy measures were participation in a *milk recording programme*, which provides feedback on milk quality; membership of a *dairy discussion/knowledge transfer group*; and whether farmers have changed the *timing of slurry spreading* on their farm to avail of greater uptake of nutrients during the early growing season (Lalor and Schulte, 2008). For cattle and sheep farms, the measures chosen were membership of a *Beef or Sheep Quality Assurance Scheme*; whether farms have undertaken *reseeding* within the last 3 yr to improve grassland performance; and whether *soil testing* has been undertaken within the last 3 yr. The measures chosen for tillage farms were availing of *forward selling* of tillage crops; extent of *usage of information & communication technology (ICT)* (such as a home computer) on the farm; and whether the farm has undertaken *soil testing* within the last 3 yr.

Aggregation of indicators

As the indicators developed in this analysis measure different concepts and use different scales, it is necessary to normalise the data and bring the various indicators to a common scale. Normalisation is performed using the MIN-MAX approach (OECD, 2008), whereby the lowest value for each indicator is subtracted from the value for a given observation and divided by the range of the dataset for that indicator. Indicators are then scaled from zero to 100, with zero indicating the poorest performance in the sample and 100 indicating the best performance. The normalised indicators are then presented using spider diagrams, which show the relative performance of the various farm systems along each dimension of sustainability.

Results

Twenty-five farm-level indicators related to the economic, environmental and social dimensions of sustainability were developed for each farm system. Results for each dimension of sustainability are presented individually and then aggregated nationally by system.

Economic sustainability

The economic indicators are presented in Table 4 (mean and s.d.) for each of the farm systems in 2012. The dairy system was the most profitable system. The proportion of output value derived from the market, as distinct from subsidies, was 85% on average on dairy farms. The indicators for cattle farms combined cattle-rearing and cattle-finishing systems. The

Table 3. Social indicators

Indicator	Measure	Unit
Household vulnerability	Farm business is not viable – no off-farm employment	Binary: 1 = yes, 0 = no
Education level	Educational attainment: 1 = primary, 2 = secondary, 3 = some agricultural education, 4 = agricultural cert., 5 = higher level	Count variable 1–5
Isolation risk	Farmer lives alone	Binary: 1 = yes, 0 = no
Demographic viability	Farmer is >60 yr old and no household member is <45 yr old	Binary 1 = yes, 0 = no
Work–life balance	Workload of farmer	Hours worked on farm/wk

average income per labour unit was higher on sheep farms than on cattle farms. On cattle and sheep farms, 60% and 55%, respectively, of the output was derived from the market, with the remainder coming from subsidies. The tillage system had the highest proportion of economically viable farms at 72% on average, followed by dairy farms at 69%, while on average, only a quarter of cattle and sheep farms were viable in 2012.

Tillage farms had the highest average income per labour unit (€43,098). However, there was considerable variation in this indicator due to differences in harvesting systems (self/contractor), with some farms achieving very high incomes (Hennessy *et al*., 2013b). Such farms had very low labour input, with most activities being contracted out. On average, in 2012, 75% of output on tillage farms was derived from the market.

The spider diagram in Figure 1 facilitates an examination of the relative economic performance of the various farm systems for each dimension of economic sustainability. On average, dairy farms, followed by tillage farms, performed better along the economic indicators relative to the other farm systems. The performance of sheep and cattle farms was very similar, although sheep systems marginally outperformed cattle systems in relation to productivity of land, productivity of labour and market profitability.

Environmental sustainability

In 2012, on average, ~61% of GHG emissions on dairy farms were generated by the dairy enterprise, with the remainder generated by cattle and other enterprises. On specialised cattle farms (which may also carry sheep), almost all of the emissions came from the cattle enterprise. Despite being specialised in sheep production, the cattle enterprise on sheep farms accounted for just more than half of sheep farm emissions. Similarly, on specialist tillage farms, the cattle enterprise accounted for almost two-thirds of emissions, while cereal enterprises accounted for only 28%. Further work is required to allocate the GHG emissions from tillage farms to the particular crops on the farm and to validate these results.

In Table 5, it can be seen that on average, dairy farms have the highest GHG emissions per farm, while cattle, sheep and tillage farm emissions are considerably lower. Emissions per farm from electricity and fuel accounted for only a small proportion of overall farm GHG emissions.

Environmental indicators cannot be separated from the economic performance of the farm as inefficient use of inputs on farms has significant economic implications for both the farmers and the wider environment. Table 5 also illustrates the usage of innovative practices across different levels of economic farm performance, where the

Table 4. Economic sustainability indicators

Farm system	Productivity of labour, mean (s.d.) (€/labour unit)	Productivity of land, mean (s.d.) (€/ha)	Market profitability, mean (s.d.) (€/ha)	Farm viability, mean (s.d.) (%)	Output derived from market vs. subsidies, mean (s.d.) (%)
Dairy	38,225 (28,034)	3,069 (984)	1,440 (619)	69 (46)	85 (7)
Cattle	15,742 (19,986)	1,251 (552)	433 (306)	25 (43)	60 (13)
Sheep	16,629 (13,975)	1,281 (599)	484 (328)	24 (43)	55 (17)
Tillage	43,098 (32,279)	1,854 (690)	840 (519)	72 (45)	74 (8)

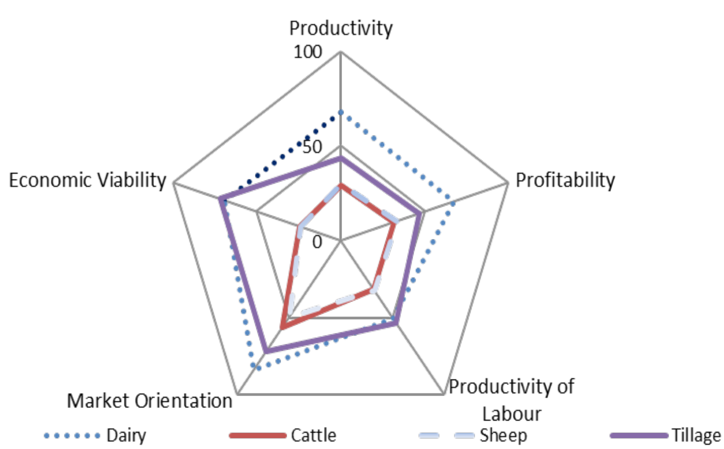

Figure 1. Economic sustainability spider diagram (spider diagrams are constructed so that zero, or poorest performance in relation to sustainability, is at the centre of the diagram and 100, or best performance, is at the outer edge).

economic categorisation of farms is based on gross margin per hectare, with weighted populations in one-third groups representing the top, middle and bottom economically performing farms.

Table 6 presents emissions per kilogram of product sold (milk, beef and lamb) relative to the economic performance of the average of the top, middle and bottom one-thirds of dairy, cattle and sheep farms (based on Gross Margins (GM) per hectare). The top economic performers in dairy, cattle and sheep farms produced the lowest emissions, and the bottom-performing group produced the highest emissions. These results show clearly the negative correlation between gaseous emissions and economic performance.

A similar trend is seen for N surplus in Table 7, where it is evident that there is considerable variation between the top and the bottom economic performers in the dairy system. The top-performing dairy farms produced a considerably larger surplus of N on average than the less profitable farms. While it is likely that these top-performing dairy farms are also more efficient in relation to N surplus generated per kilogram of product, this analysis is beyond the scope of this paper.

These results illustrate the relationship between intensity of production and economic performance as the top-performing farms produce relatively more product per kilogram of N surplus. The same trend is evident in the cattle and sheep systems, with top performers economically producing more surplus N, although with less variation between surplus N produced by the top and bottom performers. Sheep farmers on average have smaller N surpluses, particularly in the bottom group, in which some of the more extensive sheep farms have a N surplus close to zero. The N balances for tillage farms are more homogeneous than the results for livestock farms, with little variation in the mean values for the top, middle and bottom tillage groups.

From an environmental efficiency perspective, it is not very effective to compare different farm systems on an emissions-per-product basis, when the farm systems are producing very different products, i.e. kilograms of beef versus kilograms of milk. Figure 2 shows the environmental performance of all farms on the basis of their economic performance within their own farm system. In examining GHG emissions produced per unit of product, a relationship between economic and environmental performance is evident, i.e. the top-performing farms from an economic perspective produce less GHGs per kilogram of product than the bottom farms. The variation in performance is even more pronounced when GHGs from electricity and fuel are also considered.

The opposite is the case in terms of the relationship between economic performance and risk of loss of nutrients to water. There is an obvious relationship between surplus N per hectare and economic performance as N surpluses are greater for the top economically performing farms. Along this criterion, the bottom farms perform best by having the lowest N surplus per hectare.

Table 5. Environmental sustainability indicators

Farm system	GHG emissions per farm, mean (s.d.) (t CO_2eq)	GHG emissions per kg of output, mean (s.d.) (CO_2eq/kg)	Nitrogen balance per hectare, mean (s.d.) (kg of N surplus/ha)	Fuel and electricity per kg of output, mean (s.d.) (CO_2eq/kg)
Dairy	434 (246)	0.77 (0.12)	146 (63)	0.06 (0.02)
Cattle	143 (111)	12.3 (5.49)	54 (40)	0.66 (0.40)
Sheep	118 (95)	7.30 (3.51)	40 (28)	0.44 (0.25)
Tillage	139 (144)	–	53 (36)	–

GHG = greenhouse gas.

Table 6. System greenhouse gas (GHG) emissions on the basis of economic performance

Farm system	Average	Top	Middle	Bottom
Dairy (CO_2eq kg/kg of milk)	0.77	0.71	0.75	0.85
Cattle (CO_2eq kg/kg of beef)	12.30	11.32	12.41	13.33
Sheep (CO_2eq kg/kg of lamb)	7.30	5.80	7.16	9.02

Table 7. System nitrogen (N) balance (kg N surplus per ha) on the basis of economic performance

Farm system	Average	Top	Middle	Bottom
Dairy	145.5	174.9	143.4	118.5
Cattle	52.6	67.6	44.1	47.7
Sheep	38.2	49.9	40.9	23.0
Tillage	52.5	56.2	53.7	50.0

Social sustainability

The suite of social sustainability indicators developed for all the farm systems is presented in Figure 3, which shows that, in general, dairy and tillage farms perform better than the dry-stock systems along the social dimensions of sustainability. However, dairy farming is labour intensive. The work–life balance indicator is represented by the number of hours worked by the typical farm operator in an average week. On average, dairy farmers work 47 h/wk, while cattle and sheep farmers work on average 32 and 34 h/wk, respectively. Tillage farmers have the lowest average working hours at just 30 h/wk. In relation to the overlap between economic and social sustainability, as represented by farm household vulnerability, the lowest proportions of vulnerable households are in the dairy (15%) and tillage systems (18%). Vulnerability in this context means that the farm business is not viable and there is no other source of income in the household. However, the proportion of vulnerable households is much higher for the cattle and sheep systems, with more than 40% of cattle and sheep farms classified as economically vulnerable.

A similar trend is evident in relation to the age profile of farmers. In cases in which the farmer is nearing retirement but there is no obvious successor, the sustainability of farms is considered to be poor. This is the case on just 10% of dairy farms and on 20% of tillage farms, but there is evidence of poor sustainability on 28% of cattle farms and 25% of sheep farms. In relation to education, dairy and tillage farmers in Ireland tend to be better educated than other farmers. The low sustainability scoring across systems for the education indicator generally is likely to be a scaling issue as education is measured as a count variable with values from one to five. However, the differences between the farming systems are less pronounced with regard to the demographic variables; high age profile and isolation tend to vary only slightly across the systems.

Innovation

The indicators of innovation are system specific and as such are not comparable across farm systems. Figure 4 shows that adoption rates on dairy farms across the three selected

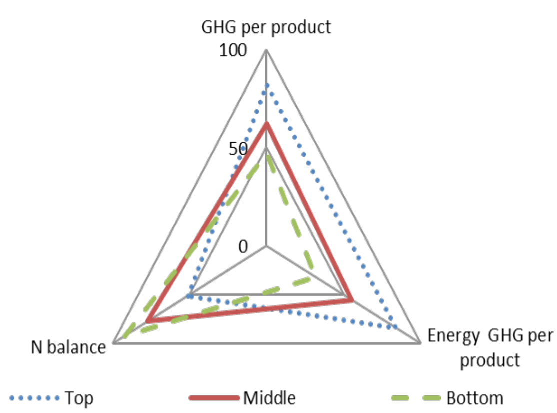

Figure 2. Environmental sustainability spider diagram.

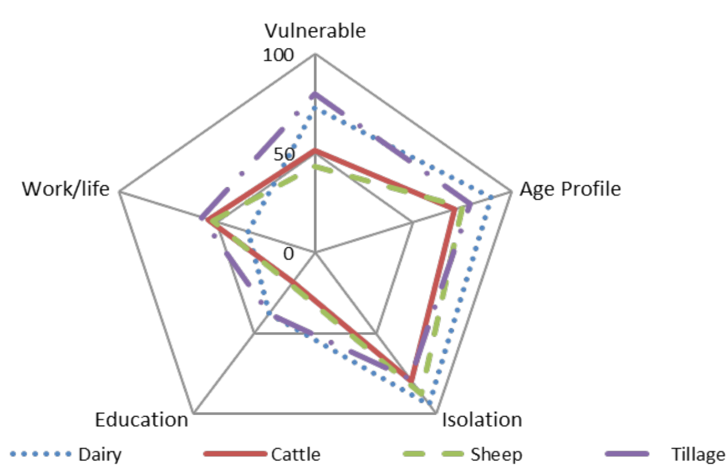

Figure 3. Social sustainability spider diagram.

practices are correlated with economic performance.

Three innovative farm practices appropriate to both cattle and sheep farms were also analysed. With regard to participation in the Beef and Sheep Quality Assurance Schemes, ~42% of cattle and 47% of sheep farms participated. As is evident from Figures 5 and 6, participation again tends to be highly correlated with economic performance. The other practices examined include soil testing and reseeding some grassland in the previous 3 yr. Adoption of these practices is also correlated with economic performance, as the top economic performers had greater rates of adoption for all three practices.

Price volatility has been a major issue confronting tillage farms in the past number of years. Forward contracting has emerged as a relatively new and innovative means of managing price risk. As can be seen in Figure 7, an average of ~30% of tillage farms entered a forward contract in 2012. There was no strong correlation between the use of forward contracting and the economic performance of the farm. In fact, the use of contracting is lowest for the top group. This may be explained by the fact that in a given year, farmers will win or lose by entering a forward contract depending on the difference between the contract price offered, which is determined by the futures price, and the actual market price. Hence, entering a forward contract can by itself determine the economic performance of the farm (Thorne, 2013). The other farm practices considered were the use of a computer for farm business purposes and soil testing. In relation to soil testing, the highest level of adoption was evident in the middle-performing cohort. However, the farms across all three economic cohorts used IT in the running of the farm.

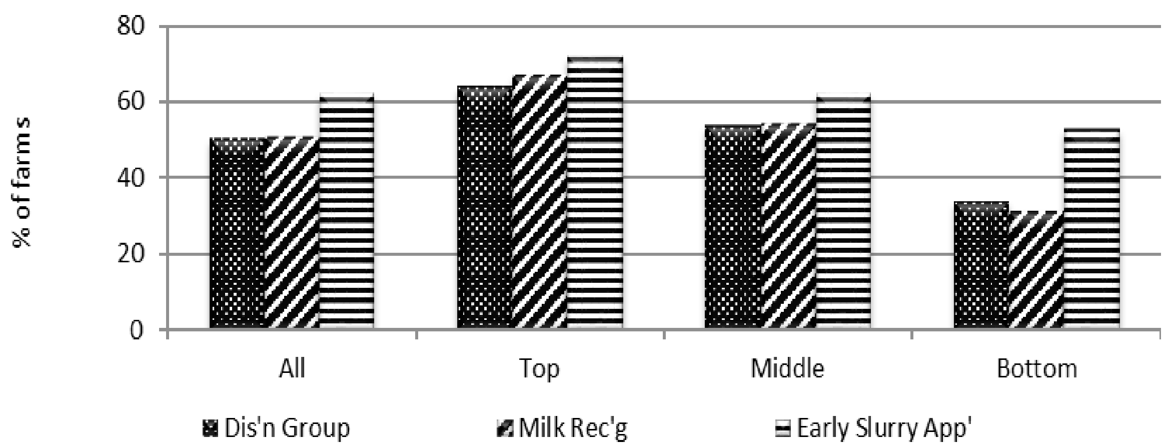

Figure 4. Adoption of innovative practices on dairy farms.
Dis’n = discussion; Milk Rec’g = milk recording; Early Slurry App’ = early slurry application.

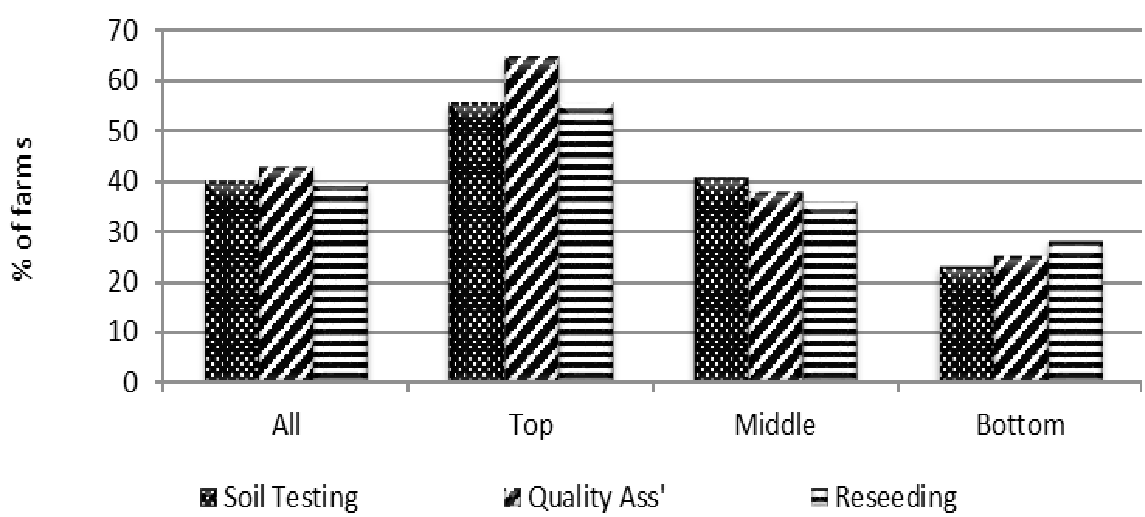

Figure 5. Adoption of innovative practices on cattle farms.
Quality Ass’ = quality assurance.

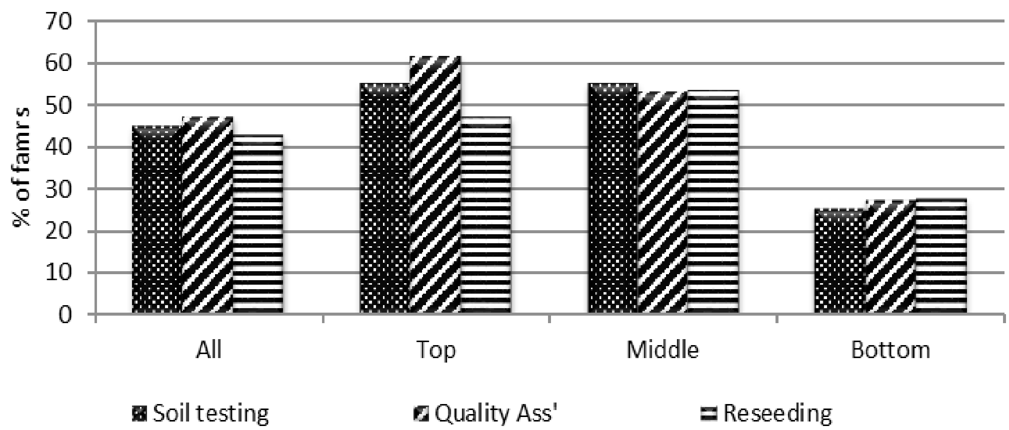

Figure 6. Adoption of innovative practices on sheep farms.
Quality Ass' = quality assurance.

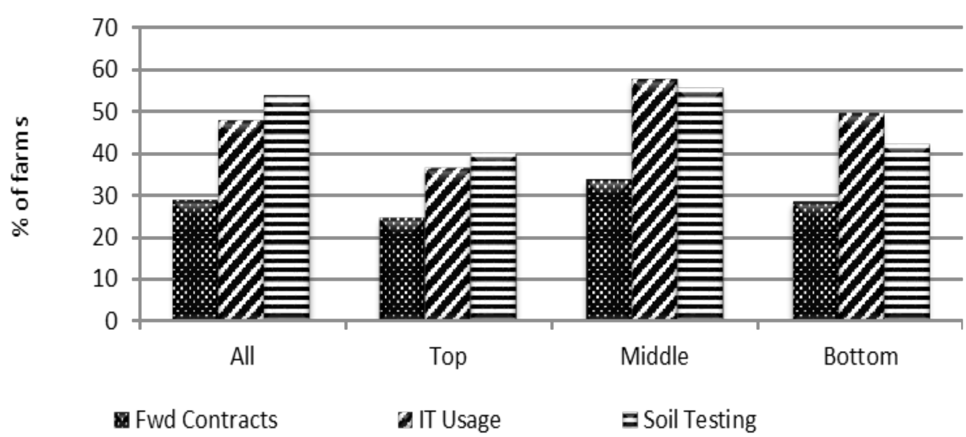

Figure 7. Adoption of innovative practices on tillage farms.
Fwd = forward; IT = information technology.

Discussion

In the context of an expanding, export-dependent agri-food sector, indicators of sustainable development and intensification are required to provide the evidence necessary to support the comparative advantage afforded by Ireland's natural food production systems. Such indicators are also necessary to ensure that we produce more food with less adverse impacts on our environment and our society. The analysis undertaken in this study shows that dairy farms, followed by tillage farms, tend to be the most economically sustainable of the four farm systems examined. Measuring emissions per unit of product allows for the incorporation of production efficiencies in indicator development.

While it is evident that intensive dairy systems produce more GHGs than other less-intensive systems, the consistent pattern across all farm systems is the positive correlation between economic performance and environmental sustainability, driven by higher output and more efficient use of inputs. The top economically performing farms tend to be the best performing farms on this aspect of environmental sustainability, as they emit relatively less GHGs per unit of product. In this case, increases in efficiency and productivity generate increased profits, without increasing negative environmental consequences. This analysis also shows that moderately economically efficient systems (middle third in terms of gross margin per hectare) appear to be more sustainable across the environmental dimension of sustainability, in particular, than less economically efficient systems. The results reveal the wide variation in environmental performance along all of the dimensions measured. In relation to risk to water quality, there is a negative correlation between economic and environmental performance, i.e. the top-performing economic farms tend to produce greater N surplus. These already intensive farmers may face the greatest challenge in expanding production without increasing the risk to water quality. However, indicators such as N balance have the potential to benchmark farms to encourage improvement in nutrient use efficiency (Buckley *et al*., 2015). Unlike the wider atmospheric impact of GHG emissions, the environmental impact of N surpluses is largely a function of localised hydrological and paedological conditions, which determine the actual risk of loss of nutrients to the local aquatic environment. Thus, the impact of N surpluses varies with specific localised conditions.

The differences in social indicators across the farm systems are not as pronounced as for the economic indicators. Dairy and tillage farms tend to be the most sustainable farms except on the work–life balance indicator, for which dairy farms have the poorest performance. Demography in particular tends to be correlated with economic performance, as the better-performing farms from an economic perspective also tend to have a younger age profile. The adoption of innovative practices was also shown to be correlated with the farms' economic performance across all systems. Wider adoption of innovative practices that increase the efficiency of resource use (land, animals, nutrients, human capital and technology) has the potential for a "win–win" outcome by not only reducing the impact on the environment but also by reducing production costs. This is evidenced by the relatively high rate of adoption of early slurry spreading on dairy farms, as this is a practice that is cost neutral to the farmer but gives both economic and environmental dividends and has been the focus of recent knowledge transfer programmes in Ireland. In an analysis of the adoption of weed management practices among Australian farmers, Llewellyn *et al*. (2006) reported that changes in the perceived short-term economic value of some weed management practices occurred in cases where the broader value of the practices to the farming system could be demonstrated. They also suggest that early identification of farmers' perceptions of the wider costs/benefits of particular farm management decisions can more effectively focus investment in research and extension.

In summary, this research shows that more-intensive farms perform best along most dimensions of sustainability, except for the risk-to-water quality indicator and the work–life balance indicator. These farms also have a higher uptake of innovative practices, improving their long-term sustainability. The corollary is that extensive farmers have a lesser impact on the environment but do not perform as well on other dimensions of sustainability. In assessing the sustainability of Irish farms across the selected indicators, it should be recognised that indicators may be in conflict with each other. The fact that a farm may be socially unsustainable (e.g. lack of successor) may actually benefit the economic sustainability of that farm system over the longer term if it leads to farm consolidation. There is also potential for conflict between economic and environmental objectives as although more intensive production tends to generate less emissions on a "per unit product" basis, it still produces more emissions overall. Given the need to increase food production, it may be desirable to focus on improving the total factor productivity, which places emphasis on all the factors of production in order to achieve more output per unit of input and per animal, thus reducing the environmental impact of expansion.

Further work

The wealth of economic data in the Teagasc NFS makes the design of economic indicators relatively straightforward, but the design of environmental and social indicators is restricted by the availability of suitable data. However, there are a number of key areas where the development of indicators is possible with the collection of additional data or further analysis.

The measurement of biodiversity is a key component of any assessment of environmental sustainability. Many Irish farming systems have a relatively high proportion of habitats for farmland wildlife (Sheridan *et al*., 2011), and this feature of Irish agriculture is a key selling point in Ireland's Origin Green international agri-food marketing campaign. Measurement of these features will be required to translate farmland wildlife attributes into labelling and marketing initiatives. Aside from its intrinsic and cultural values, biodiversity has a functional value in the provision of services, e.g. food and fuel; however, the NFS data available for this analysis did not allow for the development of biodiversity indicators. In principle, methods for the farm-scale assessment of wildlife habitats in Ireland are well developed (Sheridan *et al*., 2011), but in common with many other EU countries, the primary constraint is the logistical effort required to undertake habitat surveys. The land use types recorded in the NFS range in intensity of farming from pasture and tillage to rough grazing and old woodland and can be used to measure the richness and evenness of land use diversity. However, these data do not contain information on the relative value of each land use in terms of the ecosystem services provided. Further work needs to be undertaken to investigate the weighting of each land use type in terms of its ecological quality, before meaningful indicators of biodiversity can be developed.

Despite widespread interest in the notion of sustainability, little progress has been made towards an understanding of its social dimensions (Scott *et al*., 2000). However, the range and depth of social indicators could be improved over time to assess the social impact of agriculture at the societal level by developing indicators that measure the impact of farming and agriculture in rural areas, e.g. contribution to employment, future prospects (Vilain, 2008) and networks in rural areas, as well as membership of local and regional associations (Tömpe, 2008).

The use of innovation or practice adoption as a measure of the long-term sustainability and resilience is relatively novel (Van Galen and Poppe, 2013), and there is scope to significantly broaden this aspect in future research. As the climate change debate intensifies, the concept of Climate Smart Agriculture (CSA), which builds on SI to additionally take climate change into account, is gaining in prominence. However, according to Campbell *et al*. (2014), SI is a cornerstone of CSA as increasing resource use efficiency contributes to both mitigation and adaptation by positively affecting farm incomes and reducing emissions per unit product.

As our understanding of the interactions between the intensity of farming, its impact on the environment and climate change, and the role of innovation in these interactions becomes more important, new and more sophisticated indicators will be developed to quantify these interactions. Indicators can take account of the various dimensions of sustainability separately, or they can encapsulate all these components in frameworks of indicators. The various indicators can be combined to arrive at one indicator for each of the dimensions of sustainability, e.g. one economic, one social, one innovation and one environmental indicator per farm. It is also possible to aggregate all of these indicators to arrive at one composite measure of farm-level sustainability for each farm or for the farming sector as a whole. However, there is much debate in the literature (Gómez-Limón and Riesgo, 2009; Gómez-Limón and Sanchez-Fernandez, 2010; Reig-Martinez *et al*., 2011) surrounding the calculation and use of composite indicators, with many claiming that they oversimplify a complex issue. Further work needs to be undertaken to investigate the usefulness of composite indicators in an Irish context.

Conclusions

Indicator development is a dynamic process as, particularly in the area of environmental sustainability, novel scientific methodologies will necessitate additional data collection. As such, indicator design is evolving over time and will benefit from ongoing validation and expert consultation. Pannell (2003) notes that sustainability indicators can be used to raise awareness of resource management issues and, by providing new information, may lead to a change in management practices. While this paper describes significant progress in the development of sustainability indicators, the range of farm-level data available limits the indicators that can be currently developed, particularly in relation to the social, environmental and innovation dimensions of sustainability. While these limitations can be addressed by collecting additional data and using other datasets or expert opinion, the most valuable use of sustainability indicators lies not in the interpretation of the absolute values in any time period but in the evaluation of trends in indicators over time, which are of concern to stakeholders generally and policymakers in particular.

The use of FADN data for this type of analysis is a relatively new approach to deriving indicators along different dimensions of sustainability. At the national level, using FADN in combination with NFS data and/or expert opinion allows for the monitoring of progress towards SI and facilitates the marketing of food products, by underpinning the sustainability credentials of the Irish agri-food sector. At the European level, the linkage between NFS and FADN also presents opportunities for policy evaluation and for international comparative studies. The next phases of this work will involve (i) an extensive backcasting of historical data in order to develop a time series of national sustainability indicators and (ii) collection of supplementary FADN data to facilitate the comparison of sustainability indicators across EU Member States.

Acknowledgements

The authors wish to thank colleagues for their advice, staff involved in the collection and validation of Teagasc National Farm Survey data and the farmers who participated voluntarily in the Teagasc NFS.

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