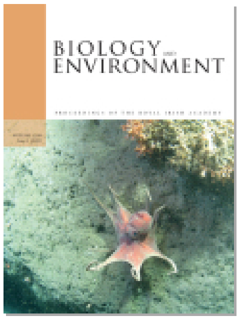
Land use and environmental quality in Ireland over two decades of contrasting agricultural trends



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LAND USE AND ENVIRONMENTAL QUALITY IN IRELAND OVER TWO DECADES OF CONTRASTING AGRICULTURAL TRENDS

Daniel Henn, James Humphreys, James Gibbons and David Styles

ABSTRACT

Global awareness and scrutiny of food production systems, including competition for land between agriculture and nature-based solutions to climate change, has increased immensely recently. In Ireland, around 70% of land area is used for agriculture, mostly pasture-based livestock production. Cattle numbers began to decline in the late 1990s, as milk productivity per cow increased along with the European Union policy of intensification implemented in 1998. Phasing out of the EU milk quota system from 2011 onwards initiated an increase in dairy cow numbers, which rose by 46% by 2020. This development has reversed environmental progress. This study outlines the impact of contrasting policies that have contributed to abatement and intensification of greenhouse gas and ammonia emissions from Ireland's agriculture, forestry and other land use (AFOLU) sector, along with impacts on water quality effects. Ireland achieved most environmental targets during the 2000s. However, between 2010 and 2019, agricultural greenhouse gas emissions increased by 12% and annual ammonia emission ceilings exceeded the national limit in seven of those years. Around 6% of rivers lost their good or high ecological water quality status. These developments jeopardise compliance with contemporary environmental targets, such as achieving a 25% reduction in greenhouse gas emissions from agriculture by 2030, and AFOLU climate neutrality by 2050. Achieving environmental quality targets will necessitate far-reaching and immediate development of policy for the land use sector beyond the implementation of currently proposed mitigation measures.

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INTRODUCTION

Modern, industrialised agriculture has a significant impact on environmental quality and land use (Springmann *et al.* 2018; IPCC 2021; Lynch *et al.* 2021). Globally, agricultural activity is estimated to account for 9.3Gt CO_2-eq. of annual greenhouse gas (GHG) emissions, with the majority being connected to methane emissions from livestock, especially bovines for beef and dairy production (FAO 2020). In addition, land use change to expand agricultural production (on pastureland or cropland for food and animal feed) often involves deforestation, contributing to GHG emissions and biodiversity loss across the globe (Lambin and Meyfroidt 2011). Animal manures and mineral nitrogenous fertiliser application are responsible for up to 90% of global emissions of ammonia. Ammonia negatively impacts air quality and contributes to particulate matter formation (Plautz 2018; Ma *et al.* 2021), damaging respiratory systems of humans and animals (Drummond *et al.* 1980; McCubbin *et al.* 2002) and vulnerable habitats such as aquatic ecosystems (Rao *et al.* 2018). In addition, excessive nutrient application to agricultural land is among the largest contributors to declining water quality globally, especially causing eutrophication through nitrogen and phosphorous leakage (Wurtsbaugh, Paerl and Dodds 2019).

There is a long tradition of pasture-based dairy and beef production from bovine animals in Ireland and accounts for 9.8% of national export value (Teagasc 2021). Since the late 1990s, the agricultural sector has been dominated by two contrasting policy developments. There was a phase of extensification in line with other European Union (EU) countries between 1998 and 2011 that put Ireland on track to meet most of its environmental quality targets. Since 2011, there has been a phase of expansion of dairy production and associated beef production (calves and culled cows) from the dairy herd. The developments have coincided with a decline in environmental quality indicators and many environmental targets have not been achieved in recent years. In 2019, Ireland's agricultural sector was identified to be responsible for 34% of national GHG emissions (Duffy *et al.* 2022) and 99% of ammonia emissions (Hyde *et al.* 2021), as well as being a major contributor to declining water quality: 55% of Ireland's water bodies are at risk of failing to meet environmental standards (DHPLG 2017).

The aim of this study is to examine the effects of contrasting policy drivers that have shaped Irish agriculture since the late 1990s and outline the factors that have impacted the sustainability of the national agriculture, forestry and other land use (AFOLU) sector. This will be compared with AFOLU sectors of other EU member states. These comparisons allow for an evaluation of where Ireland stands in terms of meeting future environmental targets, both on a national scale and within the EU. To outline and compare trends from the Irish and European AFOLU sectors, data from publicly accessible reports and databases were used to compare three well quantified environmental quality indicators (GHG emissions, ammonia emissions, and water quality) that represent the main threats to the environment associated with agriculture for which mitigation targets have been set out in regulatory instruments (Steffen *et al.* 2015).

LAND USE IN IRELAND

Agriculture is an important economic activity in Ireland occupying 70%, or 4.9 million hectares [ha], of the total land area, mainly in the form of grassland used to feed ruminant livestock (Duffy *et al.* 2022). The mild temperate and wet climate are ideal conditions for permanent grassland, which is harvested most cost-effectively by grazing livestock (Finneran *et al.* 2012; Hanrahan *et al.* 2018). Monthly average temperatures range between 5.3°C in January and 16.4°C in July. National average annual rainfall is 1,230mm (Walsh 2012). Rainfall is relatively higher during the late autumn, winter and early spring but, nevertheless, there is generally a plentiful distribution of precipitation throughout the remainder of the year. Soil moisture deficits occasionally limit pasture growth during the summer and such incidences are more frequent in the south east than in the north west. In contrast, permanent grasslands represent just 17% of land cover across all EU member states (eurostat 2022).

Ireland's forest cover has increased from 481kha in 1990 to 777kha in 2019, a rise from 6.8% to 10.9% of total land area. However, it remains far below the European average of 38% and ranks as the country with the third lowest forest cover across EU member states (Duffy *et al.* 2022; eurostat 2022). After a notable increase recorded between 1985 and 2006, with annual afforestation rates exceeding 10,000ha year^{-1}, the planting of new forested area in Ireland has since slowed. Less than 1% of total land area was afforested between 2006 and 2017 and annual rates of conversion to forestry have decreased to less than 4,000ha (DAFM 2020). The vast majority of newly afforested land between 1990 and 2019 had previously been under grassland or wetland; grassland area declined from 4.40 to 4.22 million ha and wetland area from 1.36 to 1.25 million ha during this timeframe (Duffy *et al.* 2022). In 2014, Ireland set a target to reach 18% forest cover by 2046 (DAFM 2014). To achieve this, around 18,500ha of annual afforestation is needed, vastly exceeding current afforestation rates and placing a higher burden with each passing year.

THE IRISH PASTURE-BASED BOVINE LIVESTOCK SYSTEM

Traditional livestock production in Ireland is dominated by pasture-based beef and dairy production. Between 1984 and 2015, milk output across the EU was controlled by milk quotas that were introduced to end structural oversupply that had arisen in the late 1970s and early 1980s and to cap any further expansion of EU dairy production. It set a limit on the quantity of milk that could be sold per farm within EU member states (European Commission 2015). During the late 1990s and early 2000s, reforms to the Common Agricultural Policy (CAP) promoted greater extensification of agricultural production within the EU, leading to a reduction in total cattle numbers (Humphreys 2008). Due to increasing milk yields per cow and limitations of national output imposed by the EU milk quota, dairy cow numbers declined while beef cow numbers remained unchanged in Ireland. There was a similar development across all major milk producing countries in the EU (eurostat 2022). The removal of the quota system in 2015, after gradual relaxations from 2010 onwards, coincided with an alignment of the price of milk products in the EU with markets providing the opportunity for export of EU dairy products to non-EU countries and to increase their global market share in line with growing consumer demand, especially in Asia (European Commission 2015; Grandview Research 2020). This led to an increase in raw milk production across EU-27 countries from 122Mt in 2010 to 144.2Mt in 2020, an average increase of 17.4% per country (eurostat 2022). Milk production in Ireland grew from 5.3Mt in 2010 to 8.5Mt in 2020, an increase of 60.3%, making Ireland the sixth largest producer of raw milk in the EU. The percentage increase in raw milk production within this timeframe was 13.6% in Germany, 5.6% in France, 4.1% in the United Kingdom and 20.1% in the Netherlands (eurostat 2022). While greater milk output in most other European countries was achieved primarily through increased productivity per cow, the rapid growth in output in Ireland was underpinned primarily by a growing national dairy cattle herd. This growth took place mainly on existing dairy farms leading to an intensification of land use on Irish dairy farms in general (Ramsbottom *et al.* 2020). To a lesser extent, growth in national milk production was supported by conversion of beef and tillage farms to dairy production and increased milk yields per cow. This trend was driven by profitability. Growth projections for the national dairy cow herd were considerably surpassed (Donnellan *et al.* 2018; Donnellan and Hanrahan 2011). Despite a trend towards larger farms, the total area under agricultural use remained relatively unchanged while the area farmed under derogation from the Nitrates Directive, with high organic N application rates, increased by 34% between 2014 and 2018; primarily on dairy farms (Buckley and Donnellan 2022; Nolan *et al.* 2019). Hence, the main reason for declining environmental quality indicators since 2011 is a growing intensity of emissions from dairy farms.

Average annual family farm income was €65,576 between 2011 and 2020 and substantially exceeds the average farm income of €16,880 across all non-dairy farm systems (Dillon *et al.* 2021). This income gap was a key driver of dairy expansion and for the conversion of agricultural land into dairy production, which ultimately led to a 46% growth in the national dairy cow herd, from 1,071,000 dairy cows in 2010 to 1,568,000 dairy cows in 2020 (Table 1). These developments were enabled by economic circumstances but were also actively promoted as part of national agricultural policy as outlined in documents such as Food Harvest 2020 and Food Wise 2025 (DAFF 2010; DAFM 2015). The export value of agri-food products increased from €8.5bn in 2010 to €14.1bn in 2020, an important contributor to the economic recovery after the 2008 financial crisis in Ireland. Internationally, the Irish dairy sector is competitive due to lower production costs in its largely pasture-based production systems compared with indoor- and concentrate-feed-based systems that are more typical of other EU countries. On average within the timeframe 2012 to 2017, total costs of milk production, excluding labour, were around €0.24 per litre in Ireland, compared with €0.38 in Denmark, €0.35 in the Netherlands, €0.32 in Germany, and €0.30 in the UK (Shalloo *et al.* 2020). This equated to an average net margin (excluding labour costs) of €0.08 per litre in Ireland compared with €-0.01 in Denmark, €0.036 in the Netherlands, €0.027 in Germany, and €0.046 in the UK.

As a consequence of low profitability across other farm types in Ireland, the suckler cow population decreased by 15% from 1,158,000 in 2010 to 983,000 in 2020 (Table 1), and many farms switched from suckler beef to dairy production or the marginally more profitable rearing of surplus calves from the dairy herd for beef production (Maher *et al.* 2021). Similar to other European countries, beef production from the suckler herd remains economically viable only due to direct payments under CAP that would otherwise be making a loss from cattle rearing (Dillon *et al.* 2021). A lack of profitability is also the underlying reason for a declining sheep population (Keady and Hanrahan 2016), which fell from 8.3 million in 1998 to 4.75 million in 2010 and remained at just over 5 million since 2012 (Table 1). The total number of farms across all farm types has decreased from approximately 140,000 in the late 1990s to 99,500 in 2010 and 93,200 in 2020 with a trend towards more livestock on larger farms, especially within the dairy sector (Hennessy *et al.* 2011; Dillon *et al.* 2021). Dairy farm numbers have also declined from around 25,900 in 1998 to 15,500 in 2011 (Hennessy and Kinsella 2013). However, this decline has been halted and somewhat reversed in recent years due to conversion of other farms into dairy production; the number of dairy farms has increased to 16,100 in 2020 (Dillon *et al.* 2021).

Grazed grass and grass silage account for a large proportion of the annual diet of cattle and sheep in Ireland, *c.* 82% of all dry matter intake for dairy cows (O'Brien, Moran and Shalloo 2018). The production of these forages has a high requirement for fertiliser input, particularly mineral N, and national application rates are related to total ruminant livestock, primarily cattle numbers (Table 1). The main elements applied to soils are N, P and K. Nitrogen is often the first limiting element for grass growth, and its application, most commonly as Calcium Ammonium Nitrate (CAN) and urea, aims to maximise the productivity of grassland for both grazing animals and silage production (Antille, Hoekstra and Lalor 2015).

Manure production is highly dependent on cattle numbers, especially in pasture-based production systems like Ireland where a large proportion of excreta throughout the year is directly applied to grassland soils by the grazing animals (Fischer *et al.* 2016). Increases in milk output in Ireland were primarily driven by increasing dairy cow numbers rather than yield increases per cow, indicating that manure production is coupled to this development.

Fertiliser application rates also differ across farm types (Dillon *et al.* 2018). Average mineral N application rates on dairy farms (129kg ha^{-1} in 2015) significantly exceeded those on (non-dairy) cattle (39kg ha^{-1}) and sheep (30kg ha^{-1}) farms. Similarly, the average P application rate on dairy farms (9kg ha^{-1} in 2015) was larger than on cattle (4kg ha^{-1}) and sheep (5kg ha^{-1}) farms.

ENVIRONMENTAL IMPACTS

GREENHOUSE GAS EMISSIONS

In 2019, agriculture was identified as the second largest source of GHGs in Ireland (20.48Mt CO_2-eq.), surpassed only by the (aggregated) energy sector that was responsible for 35.2Mt CO_2-eq. (Duffy *et al.* 2022). The main sources were enteric fermentation

Table 1—Annual ruminant livestock numbers [000 head] and fertiliser application rates of N and P [kt] between 1998 and 2020 in Ireland (CSO 2022; eurostat 2022).

Year	Livestock numbers				Fertiliser use	
	Total cattle	Dairy cows	Beef cows	Total sheep	N	P
	000 head				*kt*	
1998	7640	1239	1248	8312	435	50
1999	7387	1201	1217	7926	434	50
2000	7037	1178	1187	7555	398	48
2001	7050	1183	1197	7330	367	43
2002	6992	1164	1154	7209	370	42
2003	7000	1156	1187	6849	382	44
2004	7016	1156	1207	6777	360	42
2005	6992	1055	1129	6392	350	38
2006	6978	1085	1183	5973	339	36
2007	6891	1090	1207	5522	318	31
2008	6902	1095	1220	5061	308	25
2009	6891	1097	1204	4778	315	22
2010	6607	1071	1158	4745	327	28
2011	6493	1117	1123	4830	296	28
2012	6754	1141	1149	5170	311	30
2013	6903	1163	1150	5007	348	37
2014	6926	1226	1129	5097	332	36
2015	6964	1296	1076	5139	333	37
2016	7221	1398	1104	5179	339	38
2017	7364	1433	1081	5197	369	43
2018	7349	1481	1048	5109	409	46
2019	7209	1505	1000	5146	367	42
2020	7314	1568	983	5531	380	44

from cattle (59.3%), direct nitrous oxide emissions from managed soils (27.9%) and manure management (10.6%), indicating the importance of contributions from bovine livestock and the management of their manure. Compared to the European average, Ireland has an exceptional per capita emission profile. It recorded the second largest GHG emissions (12.8t CO_2-eq.) per capita across all EU member states (average 8.2t CO_2-eq.) in 2019, of which 34% originated from agriculture. The contribution of agriculture is the largest percentage of any EU member state and far above the EU average of 10.1% (eurostat 2022).

Declining cattle numbers between the late 1990s and 2011 (extensification), coincided with a decrease in agricultural GHG emissions (Fig. 1). There has been a reversal of this trend between 2011 and 2019 with increasing cattle numbers (intensification) and increasing emissions. This development contrasts with the growing global and national awareness of the climate emergency and the introduction of global goals such as the Paris agreement (UNFCCC 2015) or the net zero carbon goal by 2050 as part of the EU Green Deal (European Commission 2019b). The gap continues to widen between increasing annual emissions and the 2030 target for the Irish agricultural sector, which aims at 25% lower annual GHG emissions relative to 2018 levels (Government of Ireland 2022).

Ireland's Land-Use, Land-Use Change and Forestry (LULUCF) sector contributed annual net GHG emissions of 5.3Mt CO_2-eq. on average since 2010 (Duffy *et al.* 2022), with the main sources of emissions being drained organic soils under grassland and wetlands. Emissions of nearly 10Mt CO_2-eq. annually from these sources greatly exceed annual CO_2 removals in mineral soils under grassland, in forests and in harvested wood products (Fig. 2).

Ireland is one of few European countries with annual net GHG emissions from the LULUCF sector. In contrast, the EU-27 average annual GHG removals are *circa* 10Mt CO_2-eq. per country (eurostat 2022). Hence there is a lack of contribution from this sector to climate stabilisation goals in Ireland. This is mainly due to low national forest cover in Ireland, which is far below the average of other European countries (eurostat 2022). Average annual removals increased from -2.9Mt CO_2-eq. during the 1998 to 2009 timeframe to -4.2Mt CO_2-eq. during the 2010 to 2019 timeframe (DAFM 2019; Duffy *et al.* 2022). This is attributable to higher afforestation rates

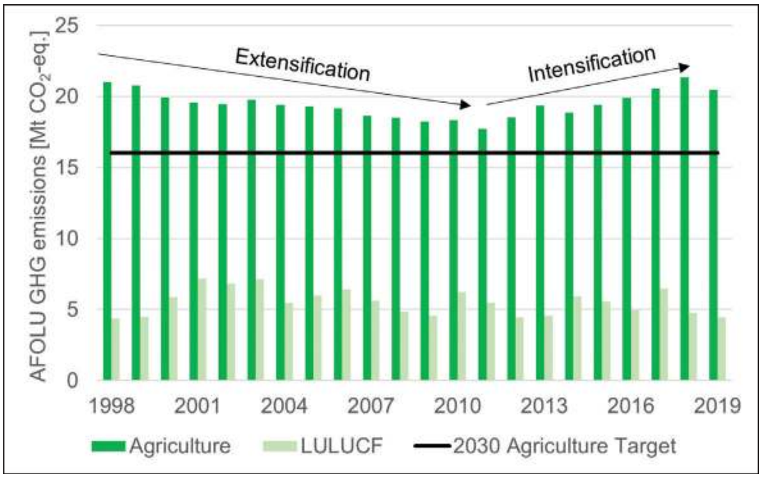

Fig. 1—Annual GHG emissions in Ireland between 2005 and 2019 (Duffy *et al*. 2022), with the 2030 GHG reduction target for the agricultural sector (25% of 2018 levels) indicated (Government of Ireland 2022).

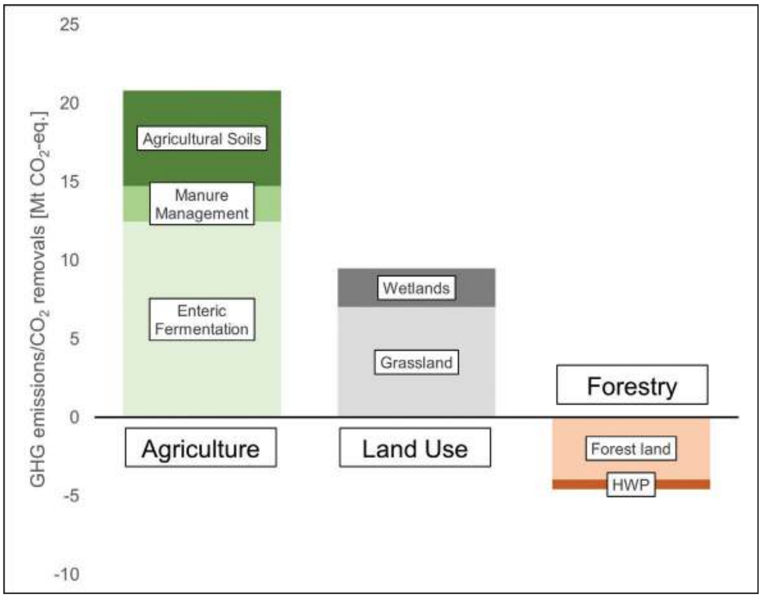

Fig. 2—Main sources of GHG emissions (positive values) and CO$_2$ removals (negative values) from the Agriculture, Forestry and Land Use (AFOLU) sector in Ireland in 2018 (Duffy *et al*. 2022). Land use are net annual CO$_2$ emissions from soils. Harvested Wood Products are abbreviated 'HWP'.

between 1985 and 2006 and a lag interval between planting and appreciable rates of CO$_2$ sequestration by the newly planted forests.

Earlier high rates of planting were achieved by planting forests on organic soils. This practice is not efficient from a GHG mitigation perspective as afforestation leads to draining of soils and subsequent lowering of the water table with significant carbon losses (Emmet-Booth *et al.* 2019). Jovani-Sancho *et al.* (2021) reported that emission factors for organic soils under forest have been substantially underestimated in Ireland, and emissions are possibly more than three times larger than currently assumed compared with the emission factors currently used in Ireland's National Inventory Report. Among the main reasons for low rates of afforestation in recent years are new opportunities in dairy production since the abolition of the milk quota and consequently greater demand for agricultural land. In addition, barriers to forestry include high administrative work (costs and licensing) and strict regulations that prevent land reversion from forestry to agriculture, which typically entails a loss of the capital values of the land, at least in the early years of plantation (DAFM 2017).

GHG emissions from grasslands in Ireland mainly originate from grassland on organic soils which are estimated to account for between 300,000 and 375,000ha (Renou-Wilson *et al.* 2015). They are typically used for extensive grazing. Over the past decade, these grassland soils have contributed net annual emissions of circa 7Mt CO_2-eq., a slight annual increase of around 0.3Mt CO_2-eq. compared to the period between 1998 and 2009 (Duffy *et al.* 2022). The latter gross emissions from grassland also include a sink of approximately -2Mt CO_2-eq. (i.e. CO_2 that is sequestered into soil carbon in mineral soils under grassland) (Conant *et al.* 2017). This sink is linked with gradually increasing intensity of grassland management in recent years, but the expansion of this sink (i.e. accounting as an annual GHG removal) has a finite duration of twenty years after the transition to more intensive grassland management, according to IPCC accounting methodology. At the end of this timeframe there will be no additional sequestration of C in these mineral soils (IPCC 2006).

Wetlands contributed average annual emissions of 2.7Mt CO_2-eq. between 1998 and 2020. They show a relatively large inter-annual variance between years that can mostly be attributed to the occurrence of wildfire events or climate dependant variables such as soil temperature and organic acid concentration in peat water (Christensen *et al.* 2003; Duffy *et al.* 2022).

AMMONIA

Agriculture is responsible for 99.4% of all emissions of ammonia in Ireland, primarily due to manure management (storage and spreading) and mineral N application to grasslands, especially urea (Hyde *et al.* 2021). The Directive (EU) 2016/2284 defines emission ceilings for each member state to reduce national emissions of atmospheric pollutants, including ammonia, based on 2005 as a reference year for emissions (European Parliament 2016). An average annual emission ceiling of 116kt was set for Ireland for the period between 2010 and 2019. National ammonia emissions declined from 126kt in 1998 to 110kt in 2011 and subsequently increased between 2011 and 2020 (Fig. 3). Since 2010, there was compliance with the emission ceiling in 2010, 2011 and 2014, while there was non-compliance for the remaining years (Fig. 3). Annual emission targets for the period between 2020 and 2029 are set at 118.4kt, and from 2030 onwards are set at 113.6kt (EPA 2021; Hyde *et al.* 2021). The Zero Pollution Action Plan (European Commission 2021) emphasises that clean air targets are currently not being met across Europe and there may be a need for stricter ammonia targets in the future.

Historic ammonia emissions were recalculated in 2021. This led to an increase in 2020 and 2030 emission ceilings, which are based on 2005 emission levels. However, 2010 to 2019 emission ceilings were not recalculated, as these years were in the past at the time of recalculations, explaining a larger emission ceiling in 2020 compared to 2010–19.

WATER QUALITY

The EU Water Framework Directive (WFD) was implemented across EU member states in the early 2000s to improve water quality across European water bodies. It provides guidelines that aim to protect all waters; including rivers, lakes, estuaries, coastal waters and groundwaters (European

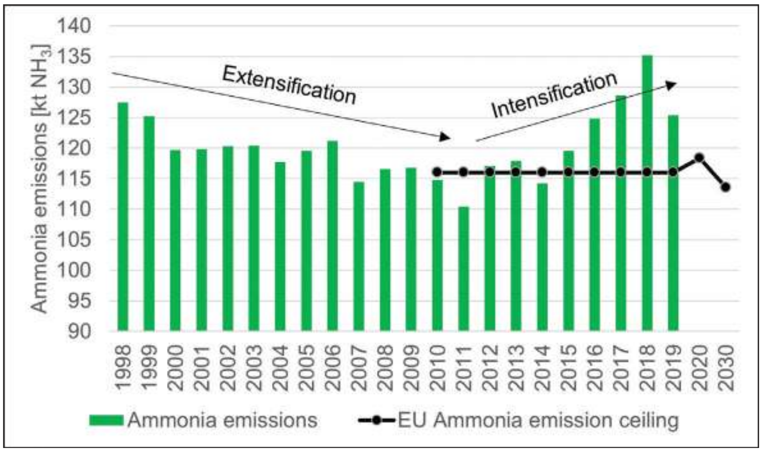

Fig. 3—Ammonia emissions in Ireland between 1998 and 2019 (Hyde *et al.* 2021), including EU emission ceilings for Ireland from 2010 and 2020, from 2020 to 2030 and from 2030 onwards according to Directive (EU) 2016/2284 (European Parliament 2016; EPA 2021). Historic ammonia emissions were recalculated in 2021. This led to an increase in 2020 and 2030 emission ceilings, which are based on 2005 emission levels. However, 2010 to 2019 emission ceilings were not recalculated, as these years were in the past at the time of recalculations, explaining a larger emission ceiling in 2020 compared to 2010 to 2019.

Parliament 2000). In Ireland, more than half of all aquatic environments at risk of not achieving the required standard of water quality receive significant nutrient loads from agriculture (O'Boyle *et al.* 2019). The two nutrients that cause eutrophication and enter water bodies from farms are N and P, which primarily originate from application of manures and mineral fertilisers (Withers *et al.* 2014).

There was a clear improvement in the ecological scores of Irish rivers between 1998 and 2011 (Fig. 4), which coincides with the period of extensification of agricultural production in Ireland. Since then, there have been significant increases in nitrate concentrations in rivers (44% between 2013 and 2019), coastal waters (24%) and groundwaters (49%) as well as phosphorus concentrations in rivers (26%), lakes (22%) and coastal waters (31%) (Trodd and O'Boyle 2020). This is despite the target of the Irish River Basin Management Plan to improve water quality across 762 of 3,206 monitored water bodies (DHPLG 2017).

However, the average ecological status of Irish water bodies improved between the first river basin management cycle from 2009 to 2015 and the second cycle from 2015 to 2021 mainly through the improvement of water bodies in poor condition at a similar rate as the European average. During the second cycle, Ireland exceeded the European share of water bodies in good or high quality by 14% (EEA 2018). A successive third river basin management cycle is expected to end in 2027, with the accompanying target to improve all water bodies to good or high ecological quality with limited availability for exemptions (European Commission 2019a).

In addition to the WFD, the Nitrates Directive aims to prevent nitrates and other pollutants from agricultural sources from entering ground and surface waters through the implementation of improved monitoring and farm management practices (European Parliament 1991). It sets limits for the annual application of livestock manure to land, periods during which spreading is prohibited and minimum capacity levels for storage of manures. Ireland's Nitrate Action Programme defines application limits of 170kg N ha^{-1} and prohibits spreading between 15 October and 12/15/31 January, depending on region, to reduce risk for environmental impacts due to high rainfall and lower grass growth rates during the winter period (DHLGH 2021). However, availing of derogation from these limits for more intensive farming practices is an option that almost 7,000 farmers chose in 2018, leading to a 34% increase in area under derogation compared to 2014 (Nolan *et al.* 2019). When derogation is granted, a higher annual application limit of 250kg ha^{-1} of organic N is permitted, allowing for more intensive farming practices. The vast majority of derogation farms are dairy farms, whose N loading per hectare surpasses all other farm types (Buckley and Donnellan 2022).

EVIRONMENTAL IMPACT DRIVERS

There are four main drivers that impact the investigated environmental quality indicators: total cattle numbers, total sheep numbers, inorganic N fertiliser use and inorganic P fertiliser use (Trodd and O'Boyle 2020; Hyde *et al.* 2021; Duffy *et al.* 2022). They represent the level of agricultural activity and intensity in Ireland (Table 1). The degree to which each of these drivers was associated with each of GHG emissions, ammonia emissions, and water quality was estimated using Pearson correlation (Benesty *et al.* 2009) across time series (1998–2019) for pairs of variables (Table 2). A strong level of correlation between the investigated time series is expected because all are related to production and animal numbers: (I) national GHG and ammonia emissions are calculated based on total livestock numbers and

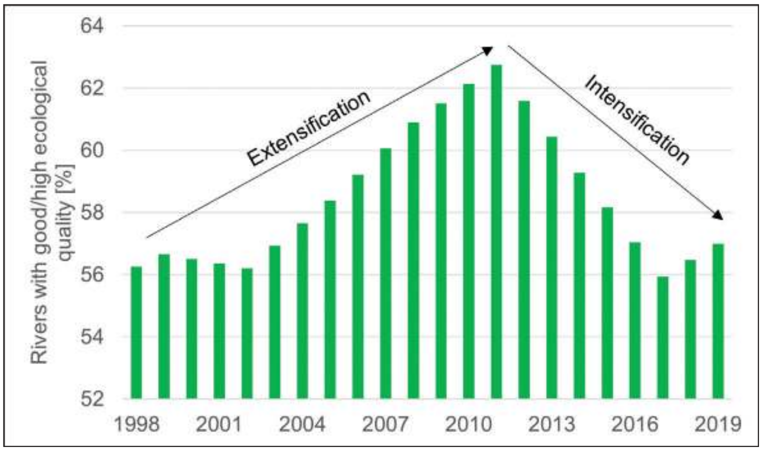

Fig. 4—Percentage of rivers with good or high ecological quality according to the Water Framework Directive definition (European Parliament 2000) in Ireland between 1998 and 2019; data was extrapolated from three-year averages presented by Trodd and O'Boyle (2021).

Table 2—Pearson correlation coefficients of time series between environmental quality indicators (agricultural GHG emissions, ammonia emissions, and water quality) and agricultural activity indicators (total cattle numbers, total sheep numbers, inorganic N fertiliser, and inorganic P fertiliser) between 1998 and 2019 ($^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; ^{NS}Not significant).

	GHG emissions	Ammonia emissions	Water quality
Total cattle	0.92^{***}	0.87^{***}	-0.82^{***}
Total sheep	0.48^{*}	0.26^{NS}	-0.64^{***}
N fertiliser	0.90^{***}	0.74^{***}	-0.81^{***}
P fertiliser	0.88^{***}	0.69^{***}	-0.90^{***}

inorganic fertiliser use, (II) N and P fertiliser use tend to be linked with each other, and (III) fertiliser use is linked to total cattle numbers due to changing grass requirements.

GHG emissions are closely correlated with total cattle numbers and inorganic fertiliser use, and less associated with dairy and beef cow numbers, indicating that differences in emission intensities from dairy or beef cattle are less important than aggregate numbers. Similarly, N and P fertiliser inputs are closely correlated with GHG emissions. A multiple regression analysis (Stolzenberg 2004) showed that total cattle numbers, total sheep numbers, N fertiliser use and P fertiliser use account for 98.5% of the variation in GHG emissions. The link between N and P fertiliser use explains the strong correlation between P fertiliser use and GHG and ammonia emissions, i.e. high P use is associated with high N use and it is the N use that increases the emissions. When removing P fertiliser inputs from the multiple regression analysis, the remaining variables accounted for 95.2% of variation, with total cattle numbers remaining the most important variable.

Ammonia emissions are closely connected with total cattle numbers and N fertiliser use. A multiple regression analysis showed that there is no combination of variables that provides a higher degree of correlation than total cattle with ammonia emissions, despite the strong correlation between N fertiliser use and ammonia emissions (Table 2). This may be explained by the dependence of N fertiliser use on total cattle numbers, as a robust proxy for agricultural activity levels in Ireland.

Water quality appears to be more independent from the investigated agricultural intensity variables. The strongest correlations were observed with P fertiliser use. Multiple regression analysis showed that P fertiliser use, N fertiliser use and total cattle numbers accounted for 88.2% of the variation. After removing N fertiliser use, 85.2% of the variation is accounted for and P fertiliser use is the most important variable. However, there may be a link between total cattle numbers and P fertiliser use due to the relationship of total cattle numbers and fertiliser use.

In all instances, total sheep numbers had a relatively small impact on the investigated environmental quality indicators. Total cattle were the main driver for GHG and ammonia emissions, while P fertiliser, also linked to total cattle numbers, is the main driver for water quality.

ENVIRONMENTAL IMPACT MITIGATION OPPORTUNITIES

AGRICULTURAL SECTOR

Effective measures to reduce GHG and ammonia emissions from the Irish agricultural sector were defined by Marginal Abatement Cost Curves (MACC) in 2018 and 2020, respectively, according to the abatement potential of their implementation and economic opportunities or costs associated with each measure (Lanigan *et al* 2018; Buckley *et al* 2020). The largest GHG emission reductions were estimated to be achievable by improving the Dairy Economic Breeding Index (EBI) of cattle, improving animal health, higher nitrogen use efficiency (NUE), increased inclusion of clover in grassland swards, increasing the proportion of protected urea replacing CAN, draining wet mineral soils and low emission slurry spreading (LESS). While the first two measures aim to reduce direct CH_4 emissions from cattle, the remaining measures are concerned with grassland management and lowering N_2O emissions. The implementation of all GHG emission abatement measures considered by the MACC outlines a pathway to reduce GHG emissions by 9% compared to the level of GHG emissions expected in 2030. Over 80% of the mitigation potential comes from the six mentioned measures (Lanigan *et al.* 2018). In relation to the 2030 target to reduce GHG emissions by 25% relative to 2018 levels, the combined MACC measures achieve a 12% reduction relative to 2018 levels. Therefore, additional action will be required to meet 2030 climate targets for the agricultural sector and it is clear that there needs to be a substantial change in emission trajectories to achieve climate neutrality by 2050. These may include new technologies such as methane reducing feed additives, whose effectiveness and scale of mitigation potential has not yet been quantified for Ireland (Government of Ireland 2021).

The primary measures to reduce ammonia emissions are the reduction of the crude protein content of dairy feed, increased inclusion of clover in grassland swards, increasing the proportion of protected urea replacing CAN, LESS and bovine feed amendments (Lanigan *et al.* 2018). The implementation of all measures outlined in the MACC would result in a reduction of 15.3 kt NH_3 from the expected ammonia emissions in 2030, sufficient to comply with the 2030 national EU emission ceiling directive reduction target (Buckley *et al.* 2020).

Water quality decline is closely correlated to P fertiliser use and total cattle numbers (Table 2). Nutrient leaching into water bodies is a more diffuse process and related to the overall intensity of agricultural activity. The impacts of certain measures on water quality trajectories are less well quantifiable compared with GHG and ammonia emissions. Measures that lower N_2O and ammonia emissions or improve the efficiency of nutrient utilisation can contribute to lower nutrient leaching. Particularly promising options include LESS and clover sward integration into grassland swards (Herron *et al.* 2021).

All environmental quality indicators are positively impacted by measures that reduce conventional CAN fertiliser application and manage slurry storage and application more efficiently. Our statistical analysis indicates that trends in total cattle numbers are likely to have been the primary driver of trends in environmental quality indicators over the past twenty years. They are the underlying reason for increasing or decreasing fertiliser application rates that further positively or negatively impact environmental quality. In coming years, a further period of intensification with growing total cattle numbers is projected (Donnellan, Hanrahan and Lanigan 2018; EPA 2022). Such a development would make it more difficult to comply with 2030 targets for climate, air quality (ammonia) and water quality. Currently suggested measures from the MACC are not sufficient to achieve the required levels of GHG emission reductions from the agricultural sector. In addition, compliance with the EU ammonia ceiling and the WFD target to improve all water bodies to good or high quality by 2027 would be hampered.

LAND USE SECTOR

To meet Ireland's 2050 climate neutrality target, the LULUCF sector will need to switch from being a net source of carbon into a net sink capable of 'neutralising' agricultural emissions and offsetting additional emissions from other sectors via large scale carbon dioxide removal (UNFCCC 2015; Huppmann *et al.* 2018). Current 'net-net' LULUCF accounting based on change in net flux relative to a reference period will soon be replaced with 'gross-net' accounting based on absolute net flux (European Parliament 2018). Hanrahan *et al.* (2021) concluded that such a change in accounting methodology would cause the combined AFOLU sector to exceed its carbon budget for most scenarios from 2026 onwards. From 2030, AFOLU will become a single sector in EU climate policy target setting, recognising the close coupling between agricultural and LULUCF sectors (European Commission 2023).

Due to declining afforestation rates in recent years, forest land is projected to turn into a net carbon source instead of a sink within this decade (DAFM 2019). This trajectory can only be prevented by improved management of existing forests (e.g. through delayed harvesting) and higher rates of new afforestation (potentially creating competition for land with agriculture). The MACC emphasises that forestry has by far the largest abatement potential of all measures from the LULUCF sector (Lanigan *et al.* 2018). In addition, commercial forestry also provides high potential to displace downstream GHG emissions from cement production and fossil fuel combustion based through use of wood-based products and fuels (Lanigan *et al.* 2018). A side effect of afforestation is the increase of direct CH_4 uptake of soils, by up to 66% in cool temperate climate zones compared to grassland soils (Yu *et al.* 2017). Soil CH_4 uptake rates are highly dependent on local conditions such as precipitation rates, atmospheric N depositions and forest management practices. They may be enhanced by up to 39% by N fertiliser addition at low application rates, while increasing global precipitation rates in cool temperate climates may decrease them (Ni and Groffman 2018; Xia *et al.* 2020). Generally, a transition from grassland to forest soil CH_4 uptake rates is of minor importance for the scale of GHG emission mitigation that is required in Ireland ($<1\%$ of required agricultural GHG emission reductions).

The impact of large-scale afforestation on water quality is largely dependent on soils and previous uses of afforested lands. Generally, forests provide opportunities for the implementation of best management practices such as riparian zones or buffer strips that reduce nutrient leaching through run-off and soils from agricultural land (Haughey *et al.* 2023). A large proportion of Ireland's recent afforestation took place on organic soils (Wilson *et al.* 2012). This practice has a much smaller positive impact on water quality (and GHG emission mitigation) compared to the afforestation of well-drained mineral soils under agricultural production (Haughey *et al.* 2023).

Agroforestry, the combination of agriculture (in the form of cropland or pastureland) and the establishment of tree cover, has particularly small adoption rates in temperate regions. The main reasons are labour costs or administrative burdens (García de Jalón *et al.* 2018). In Ireland, agroforestry occurs mainly in the form of hedgerows that provide natural boundaries for grazing livestock between fields or paddocks. Up to now, they have not been counted separately in the national GHG inventory; they are difficult to track and monitor in terms of area and growth rates (Drexler, Gensior and Don 2021; Duffy *et al.* 2022). In terms of their potential to provide additional GHG mitigation, current hedgerows that were established decades ago are a small net GHG source, largely offset by CO_2 removals into newly established hedgerows, so that overall, hedgerow carbon pools are a small (0.3 t C ha^{-1} yr^{-1}) emission source (Black *et al.* 2023).

Less intensively managed, wider and taller hedgerows could increase CO_2 removals (Black *et al.* 2023), while also being more beneficial for biodiversity and potentially mitigating nutrient leaching through improved soil structure (Montgomery, Caruso and Reid 2020; Collier 2021). Agroforestry in the form of tree or shrub cover on current grasslands is unlikely to provide substantial climate mitigation potential in Ireland. While the shade they provide may benefit animal welfare, it also reduces the productivity of grasslands, particularly of grass-clover swards (Ehret, Graß and Wachendorf 2015).

The MACC recognises wetland restoration as the second most effective GHG mitigation measure from the LULUCF sector (Lanigan *et al.* 2018). From 2025, managed wetlands will be included in climate reporting within the EU (European Parliament 2018), an additional burden to creating climate offset from the LULUCF sector. However, drained organic soils and wetlands present large potential for mitigation. This applies in particular to the 300,000 to 375,000ha of drained organic soils often used for extensive grazing, where wetting or rewetting of these soils could deliver substantial GHG emission abatement relatively quickly (Dixon *et al.* 2014; Wilson *et al.* 2016). In addition, wetlands contribute to the regulation of water quantities and nutrient leaching (Haughey *et al.* 2023).

As previously outlined, improved pastures are currently providing carbon sequestration of around 2 Mt CO_2-eq. annually after grassland intensification of about 400kha of pastureland between 2005 and 2018 (CSO 2022; Duffy *et al.* 2022). The potential for future grassland improvement to contribute CO_2 removals is constrained, especially in light of probable animal number reductions, so that this particular GHG sink cannot be relied upon to contribute to post 2050 climate neutrality. However, there are ideas that may have the potential to provide carbon sequestration in existing grasslands, for example full inversion tillage in combination with reseeding (Madigan *et al.* 2022).

Alternative uses of grass include biofuels, bioplastics, or alternative protein production to replace fossil fuels and conventional production methods (Korres *et al.* 2010; Schwinn 2019). Even though Irish grasslands offer comparatively high biomass production, they require large nitrogen fertiliser inputs under current management – making their biomass inefficient for fuel production where nitrogen is not required (unless previously extracted). Additional opportunities for use of biomass from grasslands may be biorefined products. An example is the utilisation of high-protein silage cakes as feed substitutes with a high protein content and the potential to replace protein-rich feed imports that are often associated with indirect land use change and deforestation in South America (Ravindran *et al.* 2021; Serra *et al.* 2023). Anaerobic digestion may have an important role to play in configuring efficient biorefinery value chains that extract high value products such as proteins with energy as coproducts (Jørgensen, Jensen and Ambye-Jensen 2022).

Solutions may include energy crops or short rotation coppices that accumulate biomass rapidly, and offer larger energy emission mitigation in the long-term. However, short rotation coppice willow may incur initial soil organic carbon losses during and shortly after their establishment (Clarke, Sosa and Murphy 2019), though they may provide long-term total carbon pool improvements considering aboveground, belowground biomass and an increasing soil organic carbon content over the period of a twenty-year rotation (Zang *et al.* 2018).

These alternative uses of grassland biomass or energy crops provide an opportunity to expand the Irish bioeconomy and provide income streams away from agriculture. Key requirements for successful implementation are policy-support, e.g. from the currently prepared Bioeconomy Action Plan (DECC and DAFM 2023), and investment in local infrastructure and processing capacity necessary to develop new value chains and pathways to market. Apart from biomass production, sustainable diversification may also include land rental for solar photovoltaic or wind turbine energy production, vertical farming or aquaponics (Graamans *et al.* 2018; Greenfeld *et al.* 2022). On rewetted organic soils, paludiculture or grazing where water table is not above the surface may be viable options (Rowan *et al.* 2022). A rapidly growing global market for CO_2 removal credits could generate considerable future income for Ireland's farmers through the outlined measures but may require pro-active policy oversight and support in the early stages to ensure sustainable land diversification, linked with downstream demand for new bio-products, and a just transition.

CONCLUSIONS

Diverging trends of environmental quality indicators between 1998 and 2020 have shown how agricultural production and land use in Ireland have responded to a combination of policies and market forces. During the period of extensification between 1998 and 2011, milk quotas limited the output from dairy farms while the suckler herd remained relatively stable due to generally low profitability. Higher milk yields per cow led to a constant decrease of dairy cows, a trend that was observed across Europe, and enabled land sparing for afforestation. Starting from 2011, as milk quotas started to be gradually lifted, the market began to play a greater role in the formerly policy-regulated dairy sector in Ireland. Contrary to most other European countries, dairy cow numbers have grown substantially, driven by profitability of Ireland's grazing-dominated system. Consequently, many farmers have switched to dairy farming. However, the suckler cow herd has not shrunk as much as expected when milk quotas were lifted, mainly due to subsidies that have supported the sector. Meanwhile, afforestation rates have declined.

The effects of the expansion of dairy production that was fuelled by agricultural policies are noticeable across all investigated environmental quality indicators. Greenhouse gas and ammonia emissions have significantly increased, contrary to increasing national and global ambitions to remediate the effects of global warming and air pollution. Insufficient action was taken in the land use sector and Ireland is one of very few European countries with net GHG emissions from the sector. Even though water quality has been improved from the first to the second river basin management cycles, trends show that many water bodies are vulnerable to increasing nutrient inputs, negatively affecting their ecological status. These developments are underpinned by the observed correlations between total cattle numbers and environmental quality indicators.

Considering the negative environmental impact of bovine production, especially its contribution to climate change, realigning policies to enable farmers and landowners to receive subsidies for delivering environmental services must be evaluated. This could mean accelerating the shift away from CAP pillar one payments based on agricultural activity towards payments for active land management for environmental outcomes (including afforestation and wetland restoration). Albeit challenging, this may represent the best chance to steer a just transition in rural areas while supporting the agriculture and wider land use sector on the path towards a net zero GHG emission future.

To conclude, meeting short-term (2030) and long-term (2050) environmental targets on Irish and European scale will not be possible without immediate and extensive action across Ireland's AFOLU sector. There is urgent need to gain more knowledge on the most effective land use strategies that combine agricultural activity with large-scale carbon dioxide removal to support a sustainable food system by mid-century. The development of a diversified bioeconomy that provides incentives for farmers to invest in new technologies providing income streams away from traditional grassland-based ruminant livestock production is vital to ensure the long-term sustainability of the land use sector.

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