GOBLIN scenarios to support Ireland's Carbon Budgets 3 & 4

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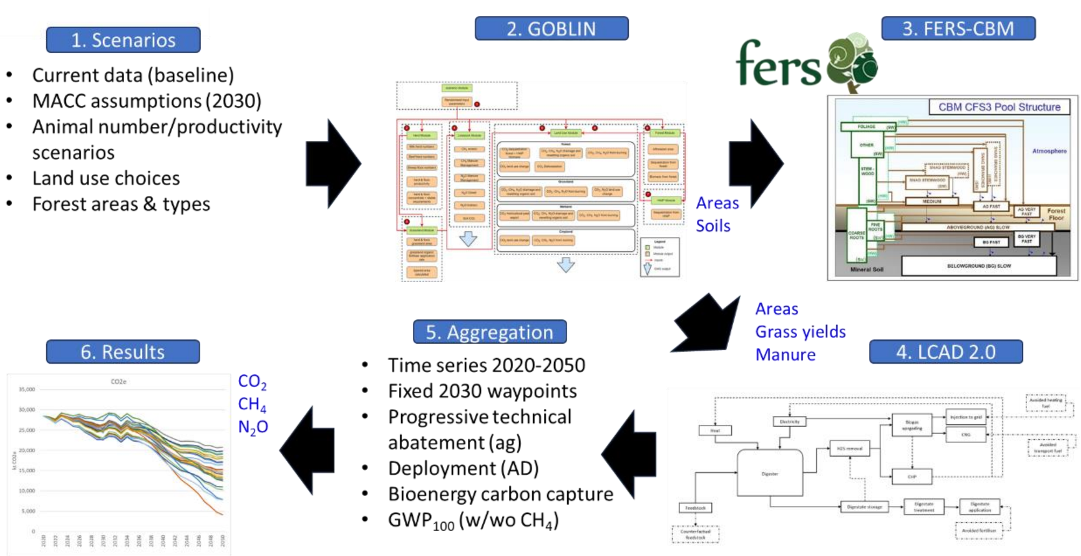

Executive summary

Greenhouse gas (GHG) emissions trajectories for the agriculture, forestry and other land use (AFOLU) sector were modelled out to the year 2100 using the GOBLIN, FERS-CBM forestry and LCAD anaerobic digestion models. Thirteen scenarios were derived to represent maintenance of bovine protein (sum of protein in milk and beef) production at 2020 levels, circa 440 kt annually (exception of "e" scenarios that reduced protein output by 19% to achieve a 60% GHG reduction for the agriculture sector by 2050). These scenarios were predicated on a strong pivot away from suckler-beef towards milk and dairy beef, and "sustainable intensification" of agricultural production to maximise animal productivity and technical abatement of GHG emissions, whilst approximately halving the area of grassland required to maintain livestock (up to 48% fewer cattle required).

Ambitious rewetting of 90% of drained organic soils under grassland and exploited peat bogs modestly reduced "other land use" GHG emissions from 7.5 Mt CO_2e in 2020 to 4.3 Mt CO_2e in 2050 (CO_2 emission reductions offset by increased methane emissions and a diminishing mineral soil carbon sink as grassland improvement effects drop out of future GHG accounting).

Sustained annual afforestation rates of 8 kha to 25 kha from 2030 to 2080 combined with carbon-enhancing forest management generated a carbon sink of 2.3 to 7.4 Mt CO_2 in new forests by 2050, somewhat offset by net emissions of circa 2 Mt CO_2e in pre-existing forests by 2050. The higher rates of afforestation are technically feasible based on areas of mineral soils spared from agriculture, but require further investigation regarding various exclusion criteria currently applied in forest licensing. Harvested wood products and bioenergy carbon capture and storage (BECCS) contributed up to 1.3 and 2.0 Mt CO_2 negative emissions by 2050. However, BECCS results are highly speculative, based on the assumption that 48% of all biogenic CO_2 from biomethane, harvested wood side streams and end-of-life wood products going to bioenergy is captured and stored by 2050. Further analysis is required to understand the economy-wide magnitude and allocation of negative emissions from BECCS, and available end-of-life wood streams, to avoid double counting across sectors. Nonetheless, results for 2100 indicate a very large technical potential for negative emissions from harvested wood products, up to 7.3 Mt CO_2e annually, that warrants further careful analysis.

No scenarios achieved a net zero emission balance (GWP100, all gases) in 2050, though three scenarios achieved a net zero balance in the mid 2060s. Meanwhile, nine scenarios achieved a GWP100 CO_2 and N_2O balance (excluding methane) by 2050, including scenario "4d" with a 50% reduction

in agricultural emissions and a sustained annual afforestation rate of 17.5 kha post 2030. This scenario could represent a reasonably robust "climate neutrality" landing zone for Ireland's AFOLU sector, based on a split gas target that recognises the powerful but short-lived warming effect of methane emission. Extreme caution is urged when applying novel methods to separate out methane from the long-lived GHGs, owing to value judgements that could unintentionally: (i) undermine economic development and food security across less economically developed countries with low methane emissions at present; (ii) further delay ramping up the afforestation carbon sink essential for robust climate action in AFOLU. This is particularly the case if a reducing rate of national methane pollution loading (from a very high per capita baseline) is equated to a national "cooling" effect, or negative emissions, as with the temperature neutrality approach in an Irish context.

2050 scenarios were used to derive emissions trajectories through the 2031-2040 carbon budget periods. It was assumed that Climate Action Plan targets were met in 2030 for the agriculture sector, for organic soils under grass and for peatlands. Derived five-year agriculture carbon budgets ranged from 68 Mt CO_2e (Sc-e, 2036-2040) to 82.4 Mt CO_2e (Sc-a, 2031-2035). Cumulative CO_2 (only) emissions represented a minor contribution of just 2 Mt CO_2 in each budget period, with little variation across scenarios.

All scenarios imply a strong consolidation of livestock rearing across fewer, highly efficient farms. Even after 134 kha of grassland are diverted to support the 5.7 TWh biomethane strategy target, and 204-576 kha are converted to forestry by 2050, up to 2 million ha of land become available for various forms of diversification – *inter alia* high nature value grassland, natural regeneration ("rewilding") or production of (low input) bioeconomy feedstocks. Elucidation of just transitions in line with these scenarios will require wider foresight analysis that includes future-oriented socio-economic assessment, and consideration of new business models to support carbon farming, payment for ecosystem services and cascading bio-based value chains. Incorporation of these aspects appears beyond the scope of current economic models, leaving a major evidence gap for strategic AFOLU policy.

1. Introduction

This report summarises the methodology, key assumptions and results, for agriculture, forestry and other land use (AFOLU) scenarios modelled within the second programme for national carbon budgets within the Carbon Budget working group. Through the working group, this modelling is intended to support Climate Change Advisory Council (CCAC) deliberations on proposals for Carbon Budget 3 (2031-35) and Carbon Budget 4 (2034-40), as per the Climate Action and Low Carbon Development Act[1].

The University of Galway (UoG) and FERS run a number of biophysical models representing greenhouse gas (GHG) fluxes for key processes in the AFOLU sector, aligned with National Inventory Report (NIR)[2] methodology for reporting Ireland's GHG fluxes to the United Nations Framework Convention on Climate Change. The two main models are GOBLIN[3] and FERS-CBM[4]. Through soft-coupling, these models were run to represent future AFOLU scenarios shaped by key assumptions outlined in this report, recent research, and specific CCAC requests.

2. Methodology

Scenarios were selected from recent GOBLIN model runs to achieve four levels of GHG reduction from agriculture relative to 2020 (30%, 40%, 50% and 60%), as requested by the CCAC. These were modelled in GOBLIN as described in section 2.1, and represent "sustainable intensification" pathways to maintain bovine protein output with fewer animals, lower emissions and less land. In parallel, a range of forestry scenarios were modelled using the FERS-CBM model to represent different types of forest management and afforestation ambition (described in section 2.2). These ran out to the year 2100 to illustrate the important long-term carbon dynamics of forest land use decisions. Emission and energy effects of anaerobic digestion (AD) of food waste, manures and grass were modelled using in the detailed LCAD 2.0 model (detailed in section 2.4). All results were aggregated, and additional post-hoc abatement or carbon capture and

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[1] https://revisedacts.lawreform.ie/eli/2015/act/46/revised/en/html

[2] https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/irelands-national-inventory-submissions-2024.php

[3] https://gmd.copernicus.org/articles/15/2239/2022/

[4] https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/carbon-accounting/carbon-budget-model/13107

storage (CCS) effects (section 2.5) were applied to generate the final emissions time series. Two different "Net Zero" climate neutrality filters were applied to GHG fluxes in the years 2050 and beyond, to provide snapshots of AFOLU climate neutrality compliance in the second half of this century:

- Net Zero GWP100: balance of CO_2e based on all GHGs accounted for using standard 100-yr GWP factors as per NIR accounting.

- Net Zero GWP100 ex methane: as above, but excluding methane from the balance, reflecting its distinct dynamics as a short-lived climate pollutant (SLCP).

The second approach is a conservative approach that anticipates separate handling of methane in future climate policy. It assumes that Ireland's emissions of methane can be reduced to a level deemed sufficient to satisfy Ireland's "fair share" to achieving global climate stabilisation, as per the Paris Agreement. This approach would involve important value judgements regarding Ireland's "fair share" of the future global methane budget for climate stabilisation[5]. Notably, application of Temperature Neutrality as an approach to determine climate neutrality, discussed at Carbon Budget working group meetings, would also involve heavy value judgement regarding Ireland's contribution to future global methane, as well as CDR, budgets (owing to implied equivalence of reduced rate of methane emission to negative emissions). These judgements require robust, careful and transparent exploration to avoid expedient but costly detours in AFOLU policy making (which urgently requires a coherent and long-term strategy).

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[5] https://doi.org/10.1016/j.jenvman.2021.113058

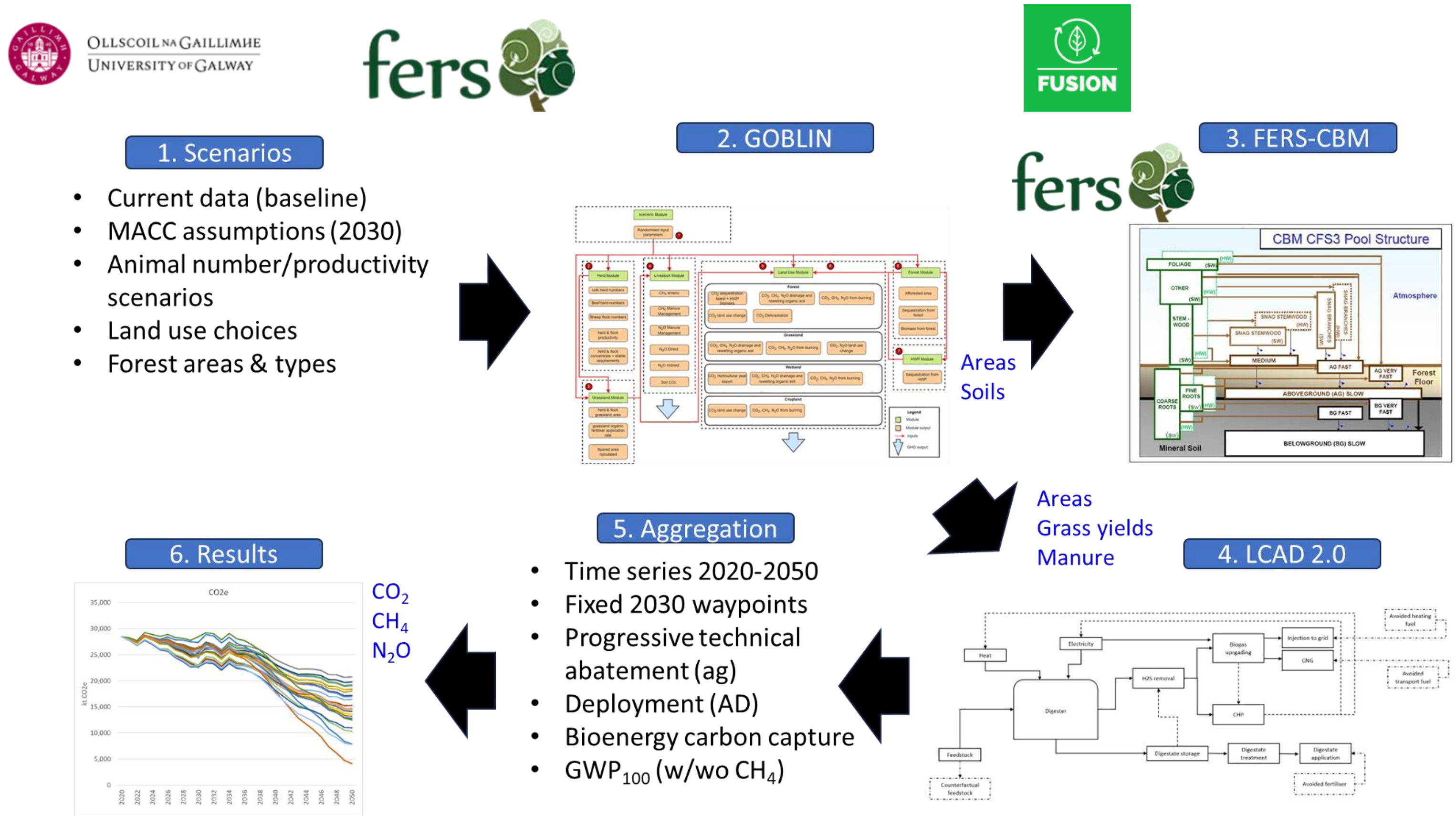

Figure 1. Data flow and modelling steps involved in generating emissions time series for AFOLU scenarios

2.1 Agriculture scenarios

Agriculture scenarios were based on recent analysis undertaken as part of a PhD thesis in the FORESIGHT modelling group (Henn, 2024)[6], in which different levels of ambition were applied to key aspects of animal breeding (productivity), management and technology driving abatement potential within the main-emitting bovine sectors of agriculture out to 2050 (Table 1). The original dataset contains 729 scenarios, representing combinations of six key AFOLU parameters evaluated at three levels of ambition (the six relevant AFOLU parameters and three levels of ambition are displayed in Table 1). GOBLIN was run for 2050 results, but emissions trajectories were forced through the 25% sectoral emission ceiling target for 2030. 2050 emissions were assumed to flatline out to 2100 in order to assess the long-term AFOLU GHG balance considering forest dynamics.

Three scenarios (a, c & d) were selected from the 2187 scenarios to approximate to agriculture sector emissions reductions of 30%, 45% and 50%. Interpolation and downscaling were used to derive two additional scenarios (b & e) corresponding to emissions reductions of 40% and 60%, completing the range of reductions sought by the CCAC (Table 2). All scenarios apart from Sc-e were based on maintaining constant level of bovine protein production in Ireland to minimise the risk of carbon leakage. Subsequent correction of cropping emissions in the scenarios altered the reductions achieved slightly to values presented in Table 3. These revisions also reduced the difference between Scenarios c & d, so c was removed.

Animal numbers and productivity

Sc-a assumes that the current cattle herd and sheep flock structure is maintained, whilst Sc-b assumes a shift out of suckler beef and towards milk plus more dairy-beef (Ambition 1 in Table 1). This reflects economic factors (dairy is far more profitable than beef farming) and future risks (and possible costs) associated with exporting a very GHG- and land- intensive product (suckler beef) from a country unlikely to achieve climate neutrality. Notably, Ireland could produce a substantial quantity of dairy beef in all scenarios, in excess of national beef demand and in excess of the ratio of beef to milk needed for a sustainable and healthy diet (Willett et al., 2019[7]; Porto-Costa et al., 2023[8]). Sc-b includes a mix of abatement parameters at Levels 2 & 3 for Table 1.

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[6]https://doi.org/10.34961/researchrepository-ul.26425558.v1
[7] https://doi.org/10.1016/S0140-6736(18)31788-4
[8] https://doi.org/10.1016/j.jclepro.2023.138826

Sc-d reduces dairy cow numbers needed to maintain bovine protein output owing to an average increase in milk productivity of approx. 4.2 litres per cow per day relative to 2020, approximating to a 1% annual increase out to 2050 (Ambition 2 in Table 1). Sc-d includes Level 3 abatement ambition (Table 1).

Sc-e scales down animal numbers, and production, from Sc-d to achieve a specified 60% reduction in agriculture sector emissions by 2050. It is therefore also dominated by Level 3 abatement ambition (Table 1).

Across all scenarios, the sheep flock is reduced by 20% to spare land, reflecting low profitability.

Average dairy and beef cow productivity scales up from current performance (Sc-a) through intermediate performance (Sc-b) to higher levels of performance (Sc-d and e) (Table 1).

Management and technologies

All scenarios involved high rates of deployment of efficient management practises and abatement technologies, proxying maximum deployment of existing proven practices and technologies by 2050. This represents a considerably higher level of emission abatement compared with the Teagasc MACC (for 2030), but is considered to be a relatively conservative approach for the 2050 timescale.

Beyond-MACC abatement is linked with management practices and technologies from the "Ambition 2" column in Table 1, including *inter alia*:

- widespread adoption of grass-clover swards to reduce synthetic nitrogen application by 75% vs 2020 (and to increase grass yields on low-input areas, sparing land).
- all residual fertiliser nitrogen being applied as protected urea.
- increased efficiency of grass(clover) utilisation by animals, from an average of 72% and 55% for dairy and beef systems in 2020, to 75% and 65% for these systems, respectively, in 2050. This reflects improved grazing management, and spares land, reducing fertiliser application rates modestly in this way.
- use of additives or boluses releasing 3-nitrooxypropanol (3-NOP) to inhibit methane from enteric fermentation by up 30%.
- Use of inhibitors or AD to reduce manure management emissions of methane by up to 75%.

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Table 1. Cattle herd numbers and abatement measures applied to critical aspects of agricultural management in randomised combinations to generate the initial dataset of 729 agriculture scenarios

Aspect	2020 Baseline (Ambition 0)	Ambition 1	Ambition 2
Livestock protein output	2020 cattle herd 2020 sheep flock 2020 dairy cow productivity (14.85 L/day)	2020 protein outputs (1.725m dairy cows and 150k beef cows) 2020 sheep flock decreases by 20% Increased dairy cow productivity (15.3 L/day)	2020 protein outputs (1.418m dairy cows and 150k beef cows) 2020 sheep flock decreases by 20% Increasing dairy cow productivity strongly (19.2 L/day)
Livestock management	2020 mean slaughter ages 2020 mean slaughter weights	Mean slaughter ages decrease by 50 days 2020 mean slaughter weights	Mean slaughter ages decrease by 100 days 2020 mean slaughter weights
Grassland sward composition and management	0% white clover swards (WCS) 100% perennial ryegrass swards (PRS) with 2020 inorganic N fertilisation rates	50% WCS without inorganic N fertilisation 50% PRS with 2020 inorganic N fertilisation rates	75% WCS without inorganic N fertilisation 25% PRS with 2020 inorganic N fertilisation rates
Fertiliser type	0% inorganic N fertiliser spread as protected urea	50% inorganic N fertiliser spread as protected urea	100% inorganic N fertiliser spread as protected urea
Grassland use efficiency	2020 dairy farm GUE (72%) 2020 beef farm GUE (55%)	Dairy farm GUE increase (75%) Beef farm GUE increase (60%)	Dairy farm GUE increase (75%) Beef farm GUE increase (65%)
Methane inhibition	0%	15% enteric fermentation 37.5% manure management	30% enteric fermentation 75% manure management

Table 2. Summary of cattle numbers and agriculture sector GHG emissions for scenarios a-e

Scenario	GHG reductions vs 2020	kt CO_2e	Dairy Cows (khd)	Suckler Cows (khd)	% change adult herd	Sheep (khd)	Bovine protein (kt yr^{-1})
Baseline	**NA**	**22,360**	**1,555**	**915**	**NA**	**2,556**	**440**
a	**-34%**	14,800	1,555	915	0	2,556	440
b	**-40%**	13,420	1,644	516	-13%	2,289	440
d	**-52%**	10,714	1,418	150	-37%	2,045	440
e	**-60%**	8,946	1,152	121	-48%	1,661	357

2.2 Forestry scenarios

Forestry scenarios 1-4 were selected based on a selection from eight scenarios run in the FERS CBM-CFS3 model[9] by FERS (Table 3), and one derivative scenario based on posthoc iteration to achieve "net zero" greenhouse gas (GHG) emissions excluding methane across the Agriculture, Forestry and Other Land Use (AFOLU) sector by 2050.

The four selected scenarios all represent "more sustainable silviculture", i.e. a reduced rate of harvest closer to the economic optimum, compared with the trend towards shorter harvest intervals (current silviculture). This applies to existing and to new forest (afforestation).

Scenario 1 represents the current policy target for afforestation of 8,000 ha per year being achieved from 2027 through to 2100, comprising a 50:50 split between slower-growing (but more biodiverse) broadleaf species and faster-growing conifer species. The soil type is split 15:85 organic:mineral soils, with significant CO_2 emissions incurred from planting on organic soils – accounted for within the forest net GHG flux results from CBM.

Scenario 2 represents an ambitious afforestation rate of 25,000 ha per year from 2031 to 2080 - spanning more than one average rotation interval in order to avoid problems with future forestry carbon dynamics, as previously highlighted in scenarios that where elevated planting rates ceased in 2050[10]. A reduced rate of afforestation from 2081-2100 is deduced to avoid exceeding a 30% national

[9] https://doi.org/10.1016/j.ecolmodel.2008.10.018
[10] https://www.nature.com/articles/s41893-022-00946-0

land share of forest cover by 2100. The species mix and soil mix is as per Scenario 1. The 25,000 ha per year afforestation rate is highly ambitious but approximates to the maximum rate achieved in the early 1990s in Ireland and technically feasible based on mineral soil areas spared from agriculture. However, various exclusion criteria currently applied in forest licensing may constrain the scale and locations of new planting.

Scenario 3 represents a scenario of maximum forest carbon sink. Afforestation rates are the same as for Scenario 2, but the species mix is weighted 70:30 in favour of fast-growing conifers, and planting on organic soils is entirely avoided.

Scenario 4 is a 70% scaled version of Scenario 3, calculated posthoc from the main scenarios modelled by FERS to achieve a "net zero" GHG balance (excluding methane) when coupled with the "d" agriculture scenario permutation (50% reduction in agricultural emissions).

All forestry scenarios include standard NIR accounting of carbon storage in harvested wood products (HWP), based on harvested volumes (which reflect management of existing and new forests, afforestation areas and species mixes) translated into HWP inputs through product breakouts, minus loss of carbon out of stored pools represented through a decay function.

However, an additional carbon storage credit was added based on escalating shares of low-value forest (bioenergy) side streams and end-of-life product (waste wood) outflows going to bioenergy with carbon capture and storage (BECCS) from 2035 onwards. Rates of BECCS deployment across bioenergy facilities were assumed to ramp up linearly from 3% of combustion CO_2 in 2035 to 90% of combustion CO_2 in 2064.

Such BECCS deployment is speculative and likely to be expensive, but could be economically attractive at future carbon prices. BECCS has been shown to increase both the magnitude and duration of climate mitigation from commercial forestry (Forster et al., 2021)[11] and is integral to climate stabilisation scenarios modelled by the IPCC (2022)[12]. However, a significant share of HWP from Irish forests are exported, and of the share that stays in Ireland, some will not be recoverable at end-of-life. Conversely, some imported wood may be available for BECCS. Thus, the BECCS estimates presented in this report are approximate upper technical bounds, and only affect the 2036-2040 Carbon Budget to a small degree – with BECCS applied to 18% of available wood by 2040 and 48% by 2050.

[11] https://www.nature.com/articles/s41467-021-24084-x
[12] 10.1017/9781009157926

Table 3. Eight scenario combinations run in FERS CBM-CFS3 model, with the four scenarios selected for CB analyses shaded. Scenario 4 is a derivative of Scenario 3 (scaled by 70%) based on posthoc iteration to achieve CO_2 and N_2O GWP100 balance in 2050.

Sc	Afforestation rate (ha/yr				Total forest area 2100	Species mix	Soil type	Management
	2024-2026	**2027-2030**	**2031-2080**	**2081-2100**	**ha**	**Broadleaf / Conifer %**	**organic / mineral %**	
	4000	8000	8000	8000	1377254	50:50	15:85	Current silviculture
1	**4000**	**8000**	**8000**	**8000**	**1377255**	**50:50**	**15:85**	**More sustainable silviculture**
	4000	8000	8000	8000	1377256	30:70	15:85	Current silviculture (high)
	4000	8000	8000	8000	1377257	30:70	15:85	More sustainable silviculture
	4000	16000	25000	10144	2300000	50:50	15:85	Current silviculture
2	**4000**	**16000**	**25000**	**10144**	**2300000**	**50:50**	**15:85**	**More sustainable silviculture**
	4000	16000	25000	10144	2300000	30:70	0:100	Current silviculture
3	**4000**	**16000**	**25000**	**10144**	**2300000**	**30:70**	**0:100**	**More sustainable silviculture**
4	**2800**	**11200**	**17500**	**7101**	**2041954**	**30:70**	**0:100**	**More sustainable silviculture**

2.3 Other land use

Across all scenarios, other land use was treated simply with an ambitious level of organic soil rewetting assumed (Table 4). Recently revised organic soil and wetland areas and emission factors from the 2024 NIR were incorporated into GOBLIN. Full rewetting was assumed to occur on 90% of the remaining drained organic soil area[13] under grass, by 2050. Similarly, 90% of remaining drained industrial and domestic exploited wetlands were assumed to be restored by 2050. A time series was generated for rewetting and restoration effects, based on linear progress towards, and from, 2030 waypoints corresponding with Climate Action Plan targets, i.e.:

- 80 kha of "reduced management intensity" (assumed full rewetting) on organic soils under grassland
- 33 kha of restoration on industrial exploited wetlands
- 30 kha of restoration on domestic exploited wetlands

It was assumed that mineral soil carbon sequestration declines to zero by 2050 as grassland improvement effects drop out of the inventory. Thus, in a simplified and conservative approach, a zero net flux was assumed for mineral soil carbon in 2050, with a linear reduction of the current 1.7 Mt CO_2e sink between 2030 and 2050.

Table 4. Areas under different organic soil and wetland categories modelled in all scenarios, for the years 2022 (last year for which inventory data available), 2030 and 2050

Land category	2022	2030	2050
		Ha	
Organic soils under grass - Drained	141 kha	61 kha	14 kha
Organic soils under grass – Rewetted	198 kha	278 kha	325 kha
Near Natural Wetlands - Drained	884 kha	884 kha	884 kha
Industrial peat - Drained	41 kha	8 kha	4 kha
Industrial peat – Rewetted	66 kha	99 ka	103 ka
Domestic drained peatland	84 kha	54 kha	8 kha
Domestic rewetted peatland	19 kha	49 kha	95 kha

[13] As of 2022 according to the 2024 NIR.

2.4 Anaerobic digestion (AD)

The modified LCAD EcoSCreen model was run to calculate the life cycle and inventory emissions consequences of digesting sufficient feedstock to generate the 5.7 TWh biomethane target set out in the Biomethane Strategy. Feedstock input prioritised readily-available waste streams, in line with maximising the climate mitigation efficacy of AD[14,15,16]. This included 75% of current food waste volumes and 75% of estimated pig and poultry slurry volumes, along with the estimated stored slurry volume generated by dairy animals (from GOBLIN). This left a requirement for grass-clover production equivalent to 9 t dry matter per hectare across 134 kha to generate the 5.7 TWh (gross) biomethane.

The AD model was parameterised to consider an optimised AD plant configuration, with closed digestate storage and comparatively low fugitive emissions of methane and ammonia, as per the most optimistic assumptions in Styles et al. (2022). Energy substitution credits were calculated based on substitution of diesel out until 2040, and natural gas (with progressive application of CCS) thereafter. However, these avoided emissions were not included in the results submitted to the CCAC as the would represent double counting. Only fugitive emissions from the AD plant and digestate handling were included in core results, along with an estimate of negative emissions associated with progressive deployment of BECCS to biomethane combusted in stationary energy generation post 2040 (at the same deployment rates assumed for wood energy - aforementioned). Highly optimistically for AD, it was assumed that the CO_2 component of biogas was also captured during biomethane purification at the prevailing CCS deployment rates through time – providing an upper-bound estimate of negative emissions potential associated with AD.

2.5 Negative emissions

All scenarios involved considerable negative emissions, generated in the land sector via afforestation, in the built environment via HWP carbon storage, and in the energy sector via BECCS. In 2050, net negative emissions from terrestrial carbon stores in forestry and HWP ranged from -1.3 Mt CO_2e for Sc-1 to -6.7 Mt CO_2e for Sc-3. BECCS contributed a further -1.5 Mt CO_2e (Sc-1) to -1.8 Mt CO_2e

[14] https://doi.org/10.1016/j.scitotenv.2016.03.236
[15] https://doi.org/10.1016/j.jclepro.2022.130441
[16] https://www.sciencedirect.com/science/article/pii/S0048969721023226

(Sc-3). These latter values are speculative and based on 48% of available wood low-value side streams and waste streams going to BECCS in 2050.

Finally, CCS application to CO_2 from biogas and biomethane combustion resulted in a negative emission of -0.41 Mt CO_2e across all scenarios. Again, this value is speculative and assumes CCS is applied across 48% of all potential biogenic CO_2 streams. Capturing all CO_2 from biogas purification to biomethane across hundreds of AD facilities may not be feasible (compared with more centralised combustion of biomethane distributed via the gas grid, and wood combusted in industrial furnaces, power stations or incinerators with CCS).

3. Results

2050 scenario results

Figure 2 provides snapshot results of AFOLU GHG fluxes across 13 scenarios for the year 2050, relative to a 2020 baseline. The level of emissions declines from scenarios "a" through to "e", reflecting a shift towards higher milk production from fewer cattle combined with more ambitious levels of technical emissions abatement (e.g. 3-NOP boluses and AD of manures). The magnitude of CO_2 sink increases from Sc-1 to Sc-3 as the level of afforestation increases, and with a high mix of fast-growing conifer species in Sc-3. Improved forest management is assumed across all scenarios to reduce net emissions from existing forests (which in any case flip from being a net sink in 2020 to a net source by 2050) and to improve the long-term mitigation profile of new forests (afforestation). Other land use emissions decline modestly from 7.5 to 4.3 Mt CO_2e, as rewetting of organic soils and peat bogs reduces CO_2 emissions but increases methane emissions, and the mineral soil carbon sequestration effect from grassland improvement diminishes through time. BECCS contributes circa 2 Mt CO_2e to negative emissions by 2050, with just over 1.5 Mt CO_2e from wood-CCS and just over 0.4 Mt CO_2e from biogas and biomethane CCS. The balance of emissions and removals by 2050 equate to net GWP100 emissions for AFOLU ranging from circa 16 Mt CO_2e in Sc-1a to just below 5 Mt CO_2e in Sc-3e. Thus, none of the modelled scenarios achieve "net zero" GWP100 for the AFOLU sector by 2050 when all gases are included (Figure 2). In fact, Sc-1, based on the current policy target for afforestation rates, does not even achieve net zero within the LULUCF sector by 2050.

If methane is excluded from the GWP100 balance, in recognition of its behaviour as a SLCP with significant ongoing emissions compatible with climate stabilisation at global scale, nine of the 13 scenarios achieve a net zero GWP100 balance across CO_2 and N_2O by 2050 – with 25 kha/yr peak forest planting of 50% (Sc-2) or 70% (Sc-3) fast-growing conifers (Figure 2). Sc-4d also achieved a net zero balance excluding methane, representing a 50% reduction in agricultural emissions combined with a peak afforestation rate of 17.5 kha/yr and 70% conifer mix.

Figure 1. GWP100 balance across the AFOLU sector including methane (top) and excluding methane (below) for the year **2050.** AFOLU balance includes prospective negative emissions from bioenergy carbon capture and storage (BECCS) applied to circa 48% of wood side streams, end-of-life wood products and biogas from anaerobic digestion. Indicative GWP100 avoidance through material and fossil energy (natural gas) substitution from wood and biomethane are shown to illustrate cross-sectoral mitigation from the land sector, but are not included in the AFOLU balance - these manifest as emissions savings/avoidance in the energy sector.

Carbon budgets

Agriculture carbon budgets range from 68 Mt CO_2e (Sc-e, 2036-2040) to 82.4 Mt CO_2e (Sc-a, 2031-2035). However, cumulative CO_2 emissions represent a minor contribution of just 2 Mt CO_2 in each budget period, with little variation across scenarios (emissions of CO_2 actually increase slightly through time owing to a shift towards abated urea fertiliser use in future scenarios). LULUCF carbon budgets range from 21.4 Mt CO_2e (Sc-3, 2036-2040) to 32.3 Mt CO_2e (Sc-1, 2031-2035). Cumulative five-year CO_2 only budgets reached as low as 2.6 Mt CO_2 (Sc-3, 2026-2040), on the way to net negative emissions by 2050 (Figure 3).

Table 5. Cumulative five-year carbon budgets for the agriculture and LULUCF sectors over the 2031-2035 and 2036-2040 budget periods, expressed as CO_2 or CO_2e (all greenhouse gases, GWP100).

		Agriculture		LULUCF	
		Mt CO_2	Mt CO_2e	Mt CO_2	Mt CO_2e
Sc-1a	2031-2035	2.0	82.4	11.8	32.3
	2036-2040	2.2	79.9	10.8	29.7
Sc-1b	2031-2035	2.0	81.4	11.8	32.3
	2036-2040	2.2	77.2	10.8	29.7
Sc-1d	2031-2035	2.0	79.3	11.8	32.3
	2036-2040	2.2	71.8	10.8	29.7
Sc-1e	2031-2035	1.9	78.0	11.8	32.3
	2036-2040	1.9	68.2	10.8	29.7
Sc-2a	2031-2035	2.0	82.4	9.5	30.0
	2036-2040	2.2	79.9	4.4	23.3
Sc-2b	2031-2035	2.0	81.4	9.5	30.0
	2036-2040	2.2	77.2	4.4	23.3
Sc-2d	2031-2035	2.0	79.3	9.5	30.0
	2036-2040	2.2	71.8	4.4	23.3
Sc-2e	2031-2035	1.9	78.0	9.5	30.0
	2036-2040	1.9	68.2	4.4	23.3
Sc-3a	2031-2035	2.0	82.4	8.8	29.3
	2036-2040	2.2	79.9	2.6	21.4
Sc-3b	2031-2035	2.0	81.4	8.8	29.3
	2036-2040	2.2	77.2	2.6	21.4
Sc-3d	2031-2035	2.0	79.3	8.8	29.3
	2036-2040	2.2	71.8	2.6	21.4
Sc-3e	2031-2035	1.9	78.0	8.8	29.3
	2036-2040	1.9	68.2	2.6	21.4

Sc-4d	2031-2035	2.0	79.3	10.4	30.9
	2036-2040	2.2	71.8	6.8	25.7

2100 scenario results

Figure 3 highlights that ongoing growth of new trees and additional forest planting post 2050 nets only modest additional increments in forest carbon storage in 2100 vs 2050, owing to the counter effect of a large increase in harvest removals by 2100. The flipside of these large harvest offtakes is a large flow of carbon into HWP and BECCS (representing 90% of bioenergy combustion in 2100, vs 48% in 2050). Thus, negative emissions are much larger by 2100, amounting to between 4.4 Mt CO_2e (Sc-1) to 7.2 Mt CO_2e (Sc-3). These negative emissions are sufficient to result in three of the 13 scenarios approximately achieving net zero including full GWP100 accounting for methane – Sc-2e, Sc-3d and Sc-3e (Figure 3). These scenarios reach net zero during the 2060-2068 period, illustrating the need to consider longer timelines for transformation of the LULUCF sector. Notably, achieving net zero GWP100 all gases would be approximately in line with the global all-gas net zero by 2070 identified as compatible with climate stabilisation at less than 2°C[17].

However, BECCS negative emissions are likely to be counted in the energy or waste sectors that capture the CO_2 at the point of combustion. Attribution of negative emissions from BECCS to offset residual AFOLU emissions, as assumed here, would require further modelling of whole-economy GHG fluxes to avoid double counting of BECCS required to balance residual emissions in the energy and other hard-to-abate sectors.

[17] https://doi.org/10.1038/s43247-023-01168-8

Figure 3. GWP100 balance across the AFOLU sector including methane (top) and excluding methane (below) for the year **2100**. AFOLU balance includes prospective negative emissions from bioenergy carbon capture and storage (BECCS) applied to circa 90% of wood side streams, end-of-life wood products and biogas from anaerobic digestion. Indicative GWP100 avoidance through material and fossil energy (natural gas) substitution from wood and biomethane are shown to illustrate cross-sectoral mitigation from the land sector, but are not included in the AFOLU balance - these manifest as emissions savings/avoidance in the energy sector (but are diminished by 2100 owing to assumption of 90% CCS application on substituted natural gas and cement production).

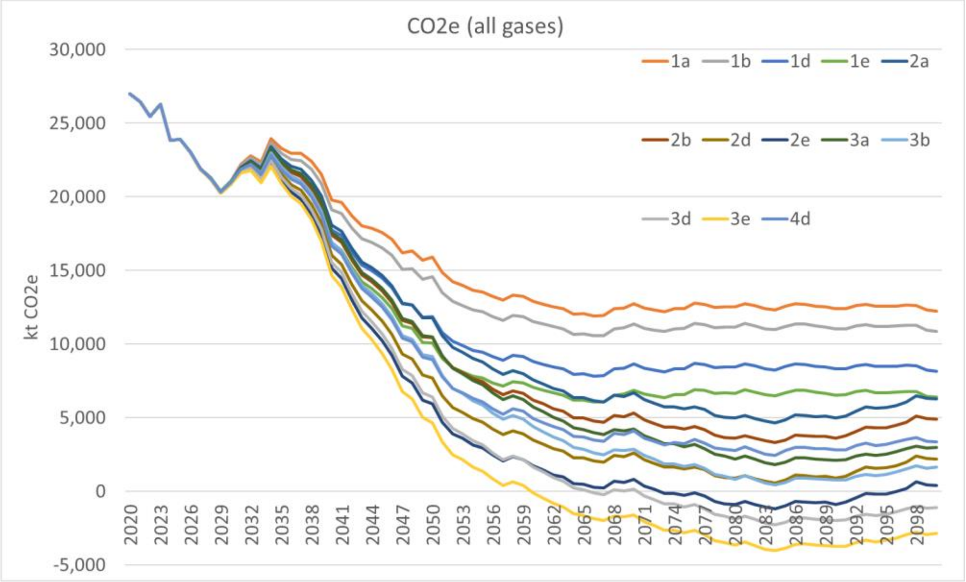

Figure 4. Net GWP100 flux (all gases) across the AFOLU sector through time for the 13 modelled scenarios.

Land use transitions

Figure 5 displays the change in land requirements between 2020 (baseline) and 2050 for the main land uses considered in GOBLIN. All scenarios spared considerable land areas owing to assumptions about improved grass use efficiency across all scenarios. Scenarios with the largest shift into milk via more productive cows (d & e) saw large reductions in overall animal numbers, especially in the beef sector, resulting in over 2 million ha of grassland being spared from animal production uses. Notably, bovine protein remained constant at 2020 levels in Sc-d, and reduced by just 19% in Sc-e. Even after accounting for the 134 kha required for grass-clover cultivation for AD, and the additional 204 kha to 576 kha required for forestry by 2050, between 328 kha (Sc-3a) and over 2 million ha (Sc-1e) of grassland were spared.

It is important to stress that results are predicated on a “sustainable intensification” paradigm, in which grassland (largely comprising grass-clover swords) is managed to be as productive as possible, with tight grazing control to increase the efficiency of grass uptake by animals (Table 1). Although not spatially explicit, GOBLIN reflects areas of the three dominant agronomic soils grades 1-3, with modified grass yield potentials. Scenario results are based on agricultural production concentrating on grade 1 and 2 soils. This implies considerable consolidation of farms into fewer, larger farms operating at high efficiency with full deployment of technical emission abatement measures.

Land spared from livestock production comprises mainly grade 2 and 3 soils. Selective afforestation on suitable mineral soils would still leave substantial areas of net spared land (Figure 5), presumably more heavily weighted in the grade 3 soil category. These areas could be suitable for, *inter alia*:

- Natural regeneration ("rewilding")
- Spreading out remaining beef and sheep production to become very extensive systems supporting high nature value grassland
- Production of bioeconomy feedstocks, including willow or other low-inputs perennial crops suited to marginal land and that could provide new habitats

Current exclusion criteria underpinning forestry licensing could be a barrier to achieving the levels of afforestation in Sc-2, Sc-3 and possibly Sc-4. Spatial modelling of AFOLU scenarios is urgently needed to identify local constraints on land use change, as well as higher resolution information on complementarities and trade-offs across climate, biodiversity and water quality effects.

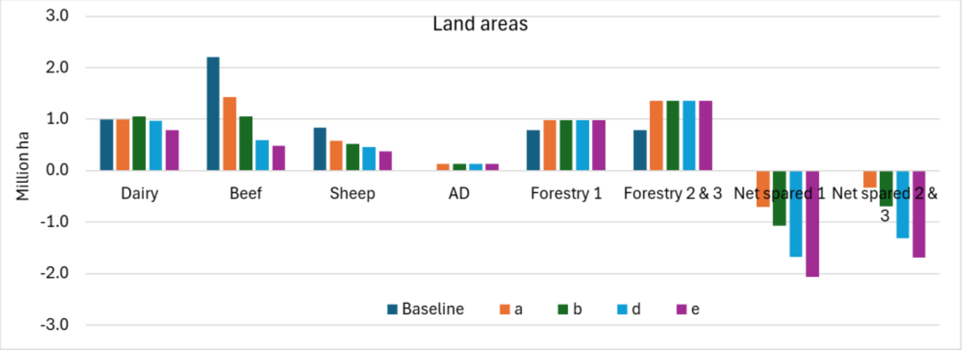

Figure 5. Baseline and 2050 scenario land requirements for main land uses, including growing grass-clover for anaerobic digestion (AD).

Scenarios presented in this report are not projections nor forecasts, but represent technically viable pathways for Ireland's AFOLU sector to continue exporting large quantities of milk and beef, in some cases within possible territorial climate neutrality constraints. The more ambitious scenarios illustrate strong potential for Ireland's AFOLU sector to play a significant role in global food security whilst protecting habitats and supplying a diversified bioeconomy. Scenarios were shaped by prioritising milk production (more profitable and land-efficient than beef production) under the “sustainable intensification” paradigm. Productivity and efficiency gains were assumed to translate into fewer animals to deliver constant protein – implying strong policy intervention to cap emissions that otherwise would be likely to increase through enhanced efficiency driving increased production. Other pathways towards climate neutrality are possible, but would require reductions in bovine protein output.

There are considerable cultural, socio-economic and possibly regulatory barriers to the magnitude of change represented by some AFOLU scenarios in this report. Overcoming these barriers may require new business models and cross-sectoral policies that disincentivise inefficient livestock rearing whilst rewarding habitat protection, carbon dioxide removal and storage (across sectors), and production and cascading use of bio-based products. The inescapable conclusion is that achieving national climate neutrality, and intermediate carbon budgets for agriculture and LULUCF, will require bold and strategic policy intervention.