



- 1 **Towards a national integrated model for land, energy, agriculture and forest systems**
- 2 **(TIM-LEAF v1.0)**
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8 Abstract

9 Achieving ambitious climate change mitigation necessitates integrated approaches across
10 energy, agriculture, land use, and forestry (AFOLU) systems. Yet, national modelling typically
11 treats these sectors in isolation and focuses on emissions rather than climate impacts. This
12 paper introduces TIM-LEAF, a national integrated modelling framework for Ireland that
13 harmonises energy, agriculture and forestry systems within a consistent modelling structure,
14 combining cost-optimisation of the energy system with simulation of AFOLU dynamics and
15 temperature response.

16 TIM-LEAF extends the TIMES-Ireland Model, a well-established national energy systems
17 model, by explicitly incorporating land resource allocation, agricultural production, forestry
18 dynamics, and inventory-aligned greenhouse gas accounting for carbon dioxide, methane
19 and nitrous oxide across energy and AFOLU sectors. Land is treated as a finite resource,
20 endogenously allocated to competing uses like bioenergy crops and forestry—subject to
21 capacity constraints and exogenous conversion rates between land types.

22 Agricultural production levels are based on national projections, and the remaining land is
23 allocated endogenously between energy crops and forestry within the optimisation
24 framework. A detailed forest module captures growth, carbon sequestration, and biomass
25 supply chains, accounting for carbon saturation effects. This enables analysis of interactions
26 between agricultural production, forest carbon sinks, bioenergy supply and energy system
27 transformation under national carbon budgets.

28 TIM-LEAF is coupled to the FaIR v2.1.3 simple climate model, enabling the evaluation of
29 multi-gas mitigation impacts on national temperature and the role of individual gases,
30 particularly methane, in shaping peak warming and overshoot dynamics. This paper thus
31 demonstrates the capabilities of TIM-LEAF and sectoral dynamics in high level scenarios.

32 The paper makes four contributions: it presents Ireland's first inventory-aligned national
33 model for these interconnected systems; introduces forest carbon dynamics within a TIMES-
34 based optimisation model; demonstrates a method for coupling national multi-gas emissions
35 pathways to a simple climate model to quantify temperature responses; and offers a
36 transferable methodological template for national-scale energy-land system integration.

37 1 Introduction

38 The global stocktake synthesis report paints a stark picture: global greenhouse gas (GHG)
39 emissions remain above levels consistent with limiting warming to 1.5 °C, and the required
40 emissions reductions are not materialising at the pace needed to achieve the Paris



41 Agreement goals (UNFCCC, 2023). Achieving net-zero carbon dioxide (CO₂) emissions by
42 2050, alongside rapid reduction of non-CO₂ gases in the near term, requires rapid
43 transformations across energy, food, land and industrial systems (UNFCCC, 2023).

44 Land resources are central to these system transformations. They underpin food production,
45 ecosystem protection and many climate mitigation strategies, including afforestation,
46 reforestation, peatland restoration, soil carbon sequestration, and harvested wood products
47 (HWP), all of which interact with land availability, agricultural production, and biodiversity
48 (IPCC, 2023). At the same time, carbon dioxide removal (CDR) options within the energy
49 system, such as bioenergy with carbon capture and storage (BECCS) and direct air carbon
50 capture and storage (DACCS) introduce additional pressures on land use and energy
51 infrastructure (Eke et al., 2025; Fajardy et al., 2019). As the scale of mitigation and carbon
52 removal increases, interactions, synergies and trade-offs across systems intensify and
53 coordinated transitions become increasingly important. Analysing these interactions requires
54 modelling frameworks that consistently represent resources, emissions and carbon flows
55 across sectors.

56 Global Integrated Assessment Models (IAMs) are valuable tools for assessing long term
57 mitigation pathways and informing global climate policy (Riahi et al., 2022), capturing key
58 interactions energy, land and climate systems across sectors and regions (Hare et al., 2018).
59 However, IAMs often simplify important country-specific characteristics—including land
60 availability, agricultural production structures, biomass supply chains and constraints in
61 energy system transformation (IPCC, 2022b). While global insights from IAMs are essential,
62 translating climate ambition into national strategies that can be implemented requires
63 modelling approaches capable of representing national circumstances in greater detail
64 (Dubash, 2023; Peters, 2024).

65 National scale modelling approaches, led primarily by energy system models (ESMs), face
66 four important limitations. First, land-use representation within ESMs remains at a nascent
67 stage despite the growing importance of land-based mitigation (Scheller et al., 2021). While
68 ESMs typically include detailed representation of energy technologies, infrastructure, energy
69 demand and CO₂ emissions arising from energy combustion, the agriculture, forestry and
70 other land uses (AFOLU) sector is typically simplified or excluded. As a result, AFOLU GHG
71 emissions—CO₂, methane (CH₄) and nitrous oxide (N₂O)—are not comprehensively
72 represented, and biogenic carbon flows from biomass production are typically overlooked,
73 potentially underestimating the climate and secondary land use impacts of bioenergy
74 systems (Searchinger et al., 2009).



75 Second, land use competition across sectors is inadequately represented. Previous studies
76 imposed land availability limits for renewable energy technologies or bioenergy production
77 (McKenna et al., 2022; Schlemminger et al., 2024), while others treated land as an
78 endogenous parameter to assess how land scarcity influences technological deployment
79 decisions in energy system decarbonization (Guillot et al., 2023; Palmer-Wilson et al., 2019).
80 Cross-sectoral approaches are less common, though some approaches impose potential
81 land restrictions to assess the interactions between energy and agricultural sectors in future
82 national energy system pathways (Heinrichs et al., 2021). However, relatively few studies
83 represent land as a shared resource; competed across energy, agriculture, forestry and
84 nature-based CDR systems, limiting the ability to evaluate trade-offs across sectors.

85 Third, national mitigation pathways are limited in the level of integration of agricultural and
86 land use mitigation with energy system mitigation strategies. While 89% of countries
87 recognize the AFOLU sector as a priority area in their Nationally Determined Contributions
88 (NDCs), the mitigation potential of the sector remains uncertain (UNFCCC, 2024). These
89 uncertainties risk overstating mitigation potential and underestimating the gap to meeting the
90 global climate goals.

91 Finally, unlike IAMs, national models do not typically represent climate outcomes associated
92 with emissions trajectories. This limits the ability to assess how the timing of emissions, CH₄
93 reductions and the contribution of individual gases in multi-gas pathways influence climate
94 outcomes including climate overshoot (Kikstra et al., 2022).

95 To address these national gaps, this paper presents TIM-LEAF, an integrated national
96 modelling framework for Ireland that extends the TIMES-Ireland Model (TIM) by linking
97 energy, agriculture and forestry systems through shared resources of land, biomass and
98 carbon alongside linking emissions to climate outcomes.

99 TIM-LEAF achieves this by 1) explicitly depicting land use across seven land types, 2)
100 including a forestry module tracking forest land dynamics, wood flows and HWP carbon
101 stock, 3) expanding the coverage of GHG sources across energy and AFOLU sectors, 4)
102 consistent accounting of emissions and removals across agricultural production and land
103 use, land-use change and forestry (LULUCF) and 5) including a simple climate model
104 (SCM), the finite amplitude impulse response model, FaIR v2.1.3 (Leach et al., 2021; Smith,
105 2023), as an extension of the core modelling framework.

106 This provides a more consistent evidence base for informing national long-term mitigation
107 strategies, while also allowing the assessment of temperature responses of multi-gas
108 emissions pathways and the contribution of individual gases to the overall temperature
109 response.



110 Ireland provides a relevant case study due to its distinctive emission profile—high reliance
111 on fossil fuels, a livestock dominated agricultural sector and emission intensive land-use
112 practices. Agriculture accounted for 37.9% of national GHG emissions in 2024, while CH₄
113 accounted for 28.7% of Ireland's total GHG emissions, with agriculture the primary source
114 and waste making a smaller contribution (EPA, 2026). Ireland's per-capita CH₄ emissions
115 are significantly higher than the global average (Duffy et al., 2025; EPA, 2026; Rogelj &
116 Schleussner, 2019). The forestry sector is transitioning from a net carbon sink to source as a
117 result of emissions from forests planted on peatlands and increased harvesting (Black et al.,
118 2025). These characteristics make Ireland an informative test case for examining
119 interactions between energy system decarbonisation, agricultural mitigation and land-based
120 carbon removals.

121 Moreover, Ireland has proposed domestic climate targets aligned with temperature neutrality
122 rather than net-zero GHGs (McMullin et al., 2025). Both the target and implications of the
123 target for specific sectors are under active debate (Duffy et al., 2025; Moriarty & Daly, 2025).

124 Existing Irish modelling frameworks provide valuable insights within their respective sectors.
125 These include the TIMES-Ireland Model (TIM), an energy system model, (Aryanpur et al.,
126 2022; Aryanpur & Rogan, 2024; Balyk et al., 2022; Daly et al., 2024; Mc Guire et al., 2023,
127 2024), the agricultural economic model, Food and Agricultural Policy Research Institute –
128 Ireland (FAPRI-Ireland; Donnellan et al., 2018) and the biophysical model, General Overview
129 of a Back-casting approach of the Livestock intensification (GOBLIN; Bishop et al., 2024;
130 Duffy et al., 2022; Styles et al., 2024). However, these models operate independently and do
131 not capture cross-sectoral interactions between the energy system, AFOLU or the emissions
132 across these systems.

133 Additionally, the temperature responses of national mitigation pathways have been used to
134 inform the development of carbon budgets (Climate Change Advisory Council, 2021, 2024;
135 Wheatley, 2023) and as a test, e.g. the Paris Test, to determine if carbon budgets and
136 resultant temperature impacts are aligned with the Paris Agreement (Climate Change
137 Advisory Council, 2021; McMullin et al., 2024; Price, 2026). However, these assessments
138 rely on outputs from multiple models, rather than a single internally consistent framework.

139 The purpose of TIM-LEAF is not to replace sector-specific models. Rather, it provides a
140 tractable integrated framework capable of analysing interactions between energy,
141 agriculture, land and forestry systems, to support integrated system analysis that was
142 previously not possible, e.g. cross-sector mitigation strategies, land constraints/competition,
143 biomass resource competition, carbon removal options and multi-gas climate outcomes,
144 within a unified modelling structure.



145 The contributions of this paper are fourfold. First, it presents the first (to our knowledge)
146 integrated, inventory-aligned national modelling platform for Ireland that represents all major
147 GHG emissions and removals across land, energy, agriculture, and forestry systems.
148 Second, it offers a methodological advance in including the afforestation, reforestation
149 approaches to CDR and carbon stock dynamics within a national TIMES-based energy
150 system optimisation model. Third, it links multi-sectoral, multi-gas pathways to the simple
151 climate model, FaIR v2.1.3, to quantify the temperature response. Finally, it provides a
152 methodological framework for other countries to analyse interactions between energy, land,
153 and agricultural systems in long-term national decarbonisation scenarios.

154 2 Model overview

155 2.1 Plain English summary

156 TIM-LEAF is a national integrated model of greenhouse gas emissions and mitigation
157 options that connects land, energy, agriculture and forestry systems within a single
158 framework. Most energy systems models focus on technologies and fuel use but do not
159 explicitly represent emissions or land use from agriculture, forestry and other land uses like
160 bioenergy and carbon dioxide removal, or how land is shared between different activities.
161 TIM-LEAF connects these sectors and activities through common resources that connect
162 them—land, bioenergy, carbon and energy. This allows the model to capture interactions and
163 trade-offs between different climate mitigation strategies, such as increasing forest carbon
164 sinks, expanding renewable energy or producing bioenergy. By representing these
165 interactions in a manner consistent with national greenhouse gas accounting, TIM-LEAF
166 offers an inventory-aligned tool for assessing the dynamics and limits of land availability,
167 biomass supply, carbon stock changes and carbon dioxide removal deployment in national
168 climate mitigation pathways. By including the FaIR v2.1.3, a simple climate model, as part of
169 the TIM-LEAF model framework, it is possible to assess the temperature contribution of
170 individual gases within multi-gas national emissions pathways.

171 2.2 Model purpose and scope

172 Future mitigation pathways require a more integrated treatment of the AFOLU and energy
173 systems, particularly to assess bioenergy potentials, waste-to-energy and circular-economy
174 options and land-use trade-offs (Balyk et al., 2022). This has motivated the development of
175 TIM-LEAF, capable of capturing feedbacks and interactions and assessing system wide
176 implications of future scenarios. Given the complexity of the AFOLU sector, the TIM-LEAF
177 model adopts a simplified yet robust national-level representation.



178 TIM-LEAF builds on the detailed bottom-up optimisation model of Ireland's energy system,
179 the TIMES-Ireland Model (TIM), inheriting its flexible spatial and temporal resolution. TIM-
180 LEAF operates at a national scale with a modelling period spanning 2018 to 2070 and is
181 solved at annual resolution. Each year is divided into 40 representative time slices capturing
182 seasonal variation, weekday/weekend patterns and intra-day load fluctuations. The model is
183 calibrated to Ireland's 2018 national energy, agricultural and forestry production balances,
184 aligned to official statistics. Historical pathways from 2018 to 2023 are simulated using
185 observed data to reflect real world developments. All costs are expressed in 2018 euros and
186 a social discount rate of 4% is applied. Modelled GHG emission pathways are translated into
187 temperature responses through the climate model.

188 2.3 Model architecture

189 TIM-LEAF is composed of four interacting systems that links the national energy system with
190 land, agriculture and forest dynamics (as shown by the integrated workflow in Figure 1):

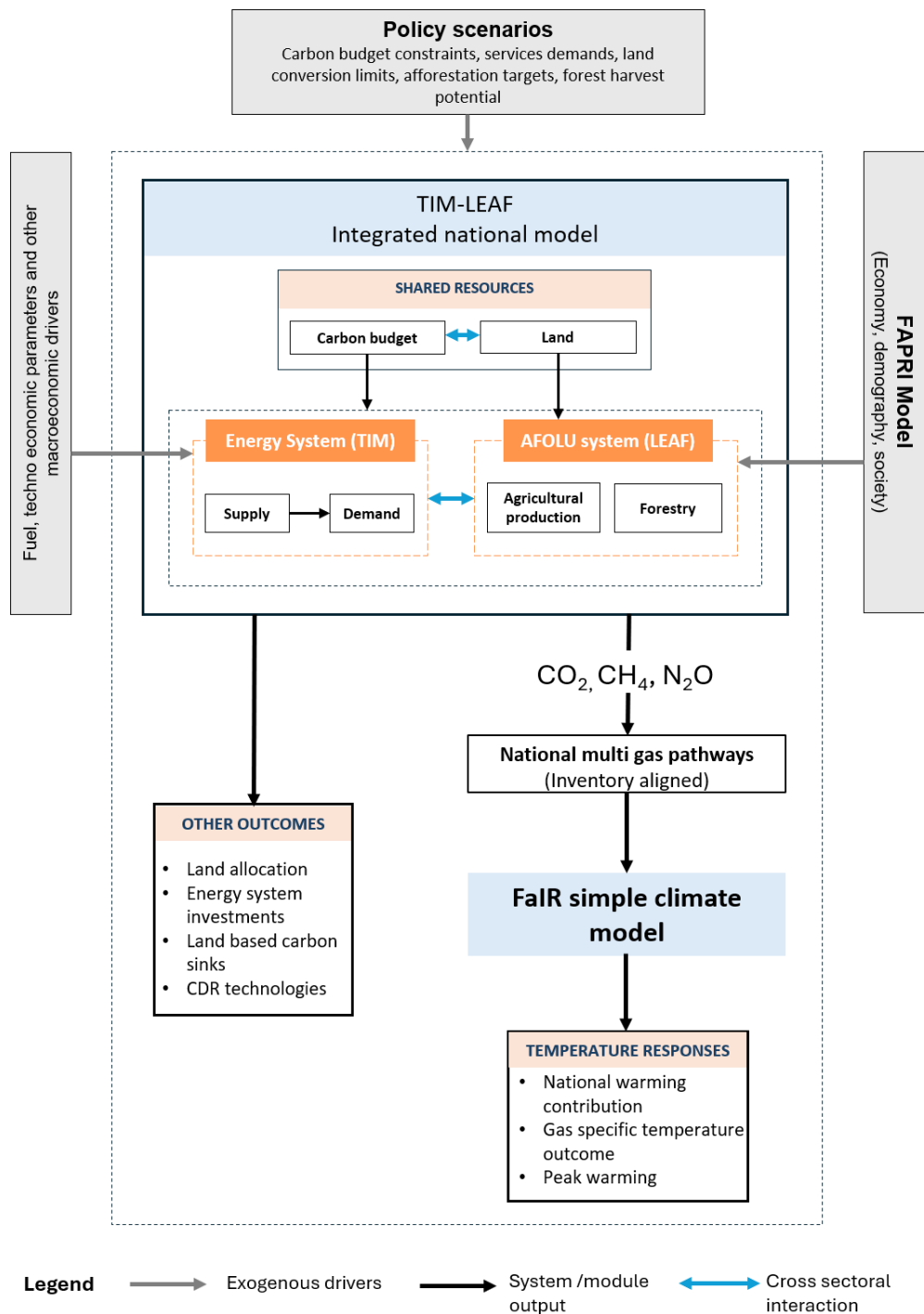
- 191 1. The energy system module represents fuel supply chains, electricity generation and
192 transmission, heat supply and energy end-use technologies to meet energy service
193 demands. It includes more than 2000 technologies and over 300 energy carriers and
194 identifies the least-cost combination of fuels and technologies under resource and
195 policy constraints.
- 196 2. Land is represented through aggregated land categories that serve as input
197 commodities for agricultural and forestry production. Land is modelled as a set of
198 national-level categories with constraints on total availability. Land-use changes are
199 governed by minimum allowable conversion shares between land types.
- 200 3. The agriculture module represents agricultural production in an aggregated macro-
201 sectoral structure. Livestock and crop production levels are defined exogenously,
202 determining the minimum land needed to satisfy agricultural service demands. On the
203 other hand, land used for bioenergy supply is determined endogenously, subject to
204 available land resources and bioenergy production costs.
- 205 4. The forestry module represents forest biomass production, harvest flows and forest
206 carbon stocks. Forest biomass supply is further constrained by sustainable harvest
207 potentials defined for different forest management practices.

208 This model structure allows land-use pathways to determine carbon stock dynamics,
209 agricultural emissions and land availability for biomass. In turn, biomass availability
210 constrains bioenergy supply to the energy system. The transformation of the energy system



211 feeds back to land use through bioenergy demand, influencing land allocation for energy
212 crops and forest biomass.

213 This integrated workflow allows CO₂ from fossil fuel combustion and CH₄ and N₂O from
214 agricultural activities and LULUCF emissions and removals to be explicitly accounted within
215 the model's GHG balance and system-wide carbon budget. Modelled emissions trajectories
216 are supplied to the SCM, FaIR, to evaluate the temperature responses of different pathways.



217

218 Figure 1: Workflow of the integrated national GHG framework, TIM-LEAF



219 2.4 Model decision structure

220 Building on the model architecture described in [Section 2.3](#), this section presents the
221 decision structure of TIM-LEAF. The following subsections describe the four core systems
222 (energy, land, agriculture and forestry), including their structural representation,
223 mathematical formulation, key data sources and assumptions. In addition, bioenergy supply
224 and GHG accounting are described as cross-cutting components that link these systems.

225 2.4.1 The energy system

226 The energy system in TIM-LEAF builds on the optimisation framework developed by (Balyk
227 et al., 2022), representing the full energy system, including primary energy supply,
228 conversion technologies, transmission infrastructure, and end-use sectors. Detailed
229 formulation and sectoral assumptions are described in (Balyk et al., 2022).

230 Within TIM-LEAF, the energy module is coupled with the AFOLU system through
231 endogenous bioenergy supply constraints. Biomass availability, including forest biomass and
232 energy crops, is determined by land availability and forest harvest dynamics in the AFOLU
233 module. These constraints determine the maximum biomass resource available to the
234 energy system.

235 Two future energy service demand scenarios are considered: a Business-as-Usual (BAU)
236 scenario, reflecting projected population and economic growth, and a Low Energy Demand
237 (LED) scenario developed by Gaur et al. (2022).

238 From 2030 onward, TIM includes carbon capture and storage (CCS) options, including
239 retrofits of existing coal, peat and gas-fired power plants. BECCS is also available, enabling
240 net-negative CO₂ removal and negative-emissions electricity generation. DACCS is
241 modelled as a backstop technology with a fixed cost of €2,000 per tonne of CO₂ in the core
242 scenarios.

243 2.4.2 The land system

244 The land system in TIM-LEAF is divided into seven land-type commodities (Table 1),
245 calibrated using National Inventory Data (NID).

246 Forest land, grassland, cropland and wetland are the primary focus of this study, as they
247 account for the majority of Ireland's LULUCF greenhouse gas fluxes and represent key
248 mitigation pathways including afforestation, grazing management and peatland restoration.
249 In the core scenarios, cropland is assumed to be in a state of equilibrium (i.e. cropland
250 remaining as cropland), reflecting limited observed land conversion in the NID. This
251 assumption can be modified through user-defined scenario inputs.



Table 1: Land types modelled in TIM-LEAF

Land type*	Description	2018 (Mha)	2020 (Mha)	2022 (Mha)
Grassland	Permanent and temporary grasslands	4.234	4.229	4.224
Cropland	Arable and horticultural land	0.747	0.747	0.747
Forest Land	Planted and naturally regenerated forests	0.771	0.776	0.780
Wetland & Peatland	Organic soils and peat areas	1.226	1.226	1.225

*Land categories follow EPA classification systems. Source: NID CRT v.2025

2.4.2.1 Land use and land-use change dynamics

The physical stock of each land type m at time t , $S_{m,t}$ is calibrated to NID land areas. The land-use module represents land allocation and land-use change dynamics across agricultural production, bioenergy production and forestry systems.

Land allocation follows a sequential structure in which agricultural land requirements are satisfied first based on exogenously specified food and livestock demand. The remaining available land constitutes a residual land pool that is allocated endogenously within the optimisation framework.

Land allocation is constrained by:

$$L_{agri,m,t} + \sum_{a \in AFOLU} L_{a,m,t} \leq S_{m,t} \quad (Eq.1)$$

Where $L_{agri,m,t}$ is the exogenously determined agricultural land requirements (Eqs. 3-4) and $L_{a,m,t}$ represents land endogenously allocated for bioenergy production and other AFOLU land use change pathways and $S_{m,t}$ is the total land area.

Land allocation to bioenergy systems is determined through system-wide cost optimisation. Decisions are made subject to land availability, competing land uses, biomass conversion efficiencies, technology costs, carbon constraints and alternative mitigation options within the wider energy system. The model therefore determines both the level and composition of bioenergy deployment, including energy crop cultivation, forest harvest rates and the level of biomass supplied to the energy sector.

In the core scenarios, upper bounds are applied to bioenergy land expansion and forest harvest levels to prevent unrealistic large-scale land conversion and biomass extraction. Table 2 summarises the land allocation logic represented within TIM-LEAF.



276 Table 2: Representation of land allocation and competing land-use pathways in TIM-LEAF

Land category	Primary function	Exogenous component	Endogenous component	Competing uses
Cropland	Food and tillage production	Food demand	Energy crops deployment	Land competition between energy crops
Grassland	Livestock and feed production	Livestock/feed demand	Grass for biogas, grassland conversion	Afforestation and biogas supply
Forest land	Managed forest system	Afforestation targets Harvest upper bounds	Harvest levels; biomass supply	Competition between harvest, afforestation and alternative land uses
Wetland	Wetland ecosystems	-	-	Wetland to forest conversion

277 Land-use change is represented through a stock-flow formulation:

$$278 \quad S_{m,t+1} = S_{m,t} + \sum_{n \neq m} CON V_{n \rightarrow m,t} - \sum_{n \neq m} CON V_{m \rightarrow n,t} \quad (Eq.2)$$

279 This formulation conserves total land area while allowing transitions between land categories
 280 over time. Historical land-use transitions for 2018–2023 are calibrated using NID CRT Tables
 281 4.A–4. F, distinguishing between land that remains the same type and land that is converted.

282 To be consistent with observed historical land use change dynamics, minimum conversions
 283 limits are defined for the historical years (2018-2023). These limits ensure that the model
 284 reproduces historical land changes while allowing future land use dynamics to be
 285 endogenously determined.

286 Over the modelling horizon, land use transitions are governed by availability of suitable land
 287 categories and competing demands. For example, afforestation or bioenergy expansion can
 288 utilise available residual land resources but cannot exceed the physically available area
 289 within each land category. Upon exhaustion of land resources are exhausted, additional
 290 expansion of the associated activity is constrained.



Table 3: User-defined land conversion constraints applied in core scenarios

From	To	Min conversion limit (Mha)
Grassland	Forest land	0.155
Wetland	Forest land	0.106
Forest land	Grassland	0.007
Forest land	Wetland	0.003

2.4.3 The agricultural system

The agricultural module comprises three sub sectors: livestock production, tillage production and energy crops, carrying forward a previously developed Agri-TIMES module (Chiodi et al., 2016). Agricultural production is driven by 12 specified service demands. Base-year values are calibrated using Central Statistics Office agricultural data (CSO, 2024, 2025) and FAPRI model projections (Lanigan et al., 2024). Each agricultural activity is characterised by its technical parameters (efficiency and energy use) and environmental attributes (land use, process and land use emission intensity).

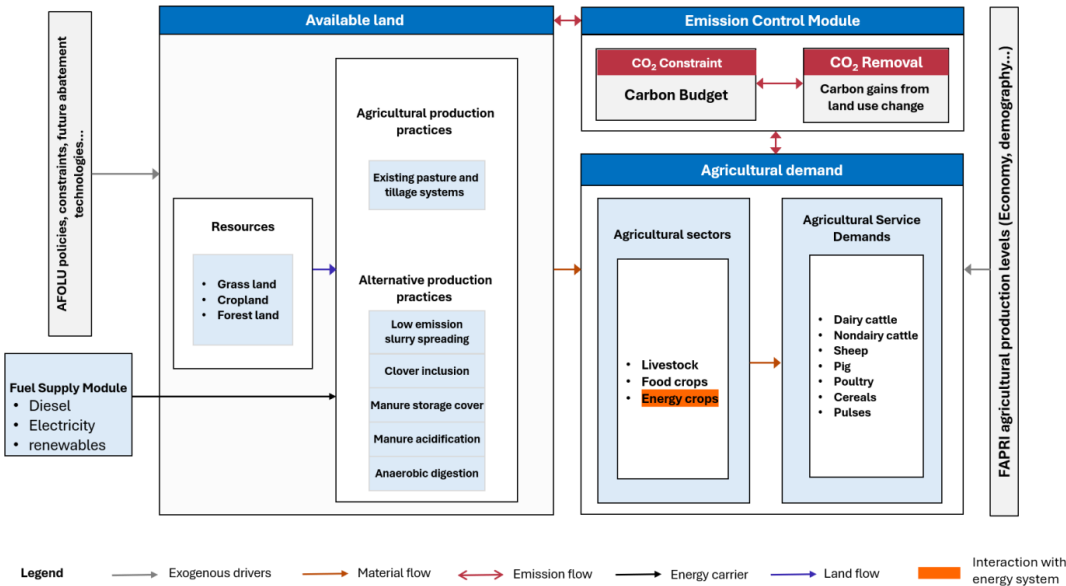


Figure 2: Simplified agricultural structure in TIM-LEAF, adapted from the original Agri-TIMES model in Chiodi et al. (2016).



2.4.3.1 Agricultural land use

For livestock systems, required grassland area is determined by:

$$L_i = \frac{P_i}{SR_i \times LU_i} \quad (Eq. 3)$$

for pasture systems (L_i , ha) for each livestock category i . P_i is the livestock population (head), SR_i is the stocking rate (livestock unit per hectare), LU_i is the livestock-unit coefficient used to normalise animal by feed requirements. When stocking rate is expressed in head per hectare, the LU term is omitted. Empirical parameters are drawn from national and regional datasets: animal populations from Central Statistics Office database (CSO, 2025), stocking rates for dairy cattle, non-dairy cattle and sheep stocking rates from Teagasc farm survey reports (Teagasc, 2022c, 2022a, 2022b), derived assumption for other animals based on (García et al., 2005; Irish Native Rare Breed Society, n.d.; Mellado et al., 2003) and the LU conversion factors from Eurostat database (Eurostat, 2026).

For crop systems, land demand is defined as:

$$L_j = \frac{Q_j}{Y_j} \quad (Eq. 4)$$

where Q_j is the annual production (tonnes) and Y_j is the harvest yield (tonnes per ha). Both parameters are sourced from CSO crop production statistics.

Total agricultural land demand is then given by:

$$L_{agri,m,t} = \sum_{i \in I} \frac{P_i}{SR_i \cdot LU_i} + \sum_{j \in J} \frac{Q_j}{Y_j}$$

2.4.3.2 Agricultural system assumptions

• Future projections

Baseline agricultural activity follows FAPRI-Ireland projections for 2018–2050 (Lanigan et al., 2024). Beyond 2050, production levels are held constant through to 2070.

A low-demand scenario is also defined to represent structural change in the agricultural sector. This pathway reflects reduced livestock production and a shift towards increased cereal output. Cereal area development follows FAPRI projections (Lanigan et al., 2024), while dairy and non-dairy cattle are assumed to decline by 50% by 2050 relative to 2022 levels. Projections for other livestock and agricultural productions are based on own assumptions, following the pattern from 2013 to 2021 (CSO, 2024, 2025).



Table 4: Agricultural service demands FAPRI-model projections

Category	Unit	2018	2022	2030	2040	2050
Baseline scenario						
Non-dairy cattle	000 head	5836	5742	5256	5125	4993
Total cereal area	000 ha	261	286	283	249	229
Milk production	Million litres (Ml)	8133	9442	10433	12346	13003
Agricultural low demand scenario						
Non-dairy cattle	000 head	5836	5742			2871
Total cereal area	000 ha	261	286	287	260	246
Milk production	Million litres (Ml)	8133	9442			4721

• Future technology options

Agricultural mitigation options are selected using marginal abatement cost (MAC) curves developed by Teagasc (2023). These represent a range of mitigation potentials across different technology readiness levels:

- i. Established measures—low-emission slurry spreading (LESS), incentivised through national grant schemes (DAFM, 2023c).
- ii. Mature options: clover inclusion and manure storage cover.
- iii. Advanced mitigation options: manure acidification, anaerobic digestion and methane inhibitors which provide higher methane abatement potential but require greater investment and infrastructure. Anaerobic digestion additionally provides co-benefits through renewable biogas production.

• User constraints

Adoption of agricultural mitigation technologies in TIM-LEAF is influenced by the marginal abatement costs, uptake dynamics and deployment limits capping the maximum share of technology rollout. For anaerobic digestion no cost is assumed, the model deploys livestock–anaerobic digestion systems if combined heat and power (CHP) plants capable of utilising the resulting biogas are economically viable within the energy system. Mitigation technologies are not applied uniformly across all livestock categories; they are targeted to livestock where production is more intensive.



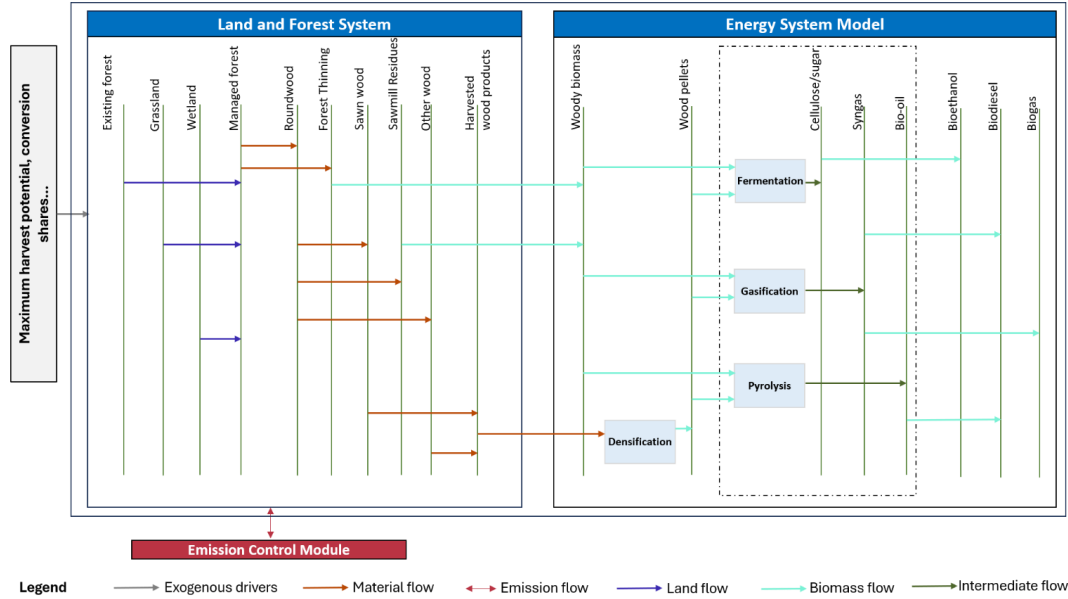
352 Table 5: Agricultural mitigation options included

Mitigation option	Livestock targeted	Emission reduction
Low-emission slurry spreading	Dairy/non-dairy cattle, sheep	45% reduction in N ₂ O: Own assumptions, based on (Efosa et al., 2025; Hafner et al., 2025; Teagasc, 2020)
Clover in pastures	Dairy/non-dairy cattle, sheep	40% reduction in N ₂ O emissions for dairy pastures (Teagasc, 2022d) Assume the same for non-dairy and sheep pasture systems)
Manure storage covers	Dairy/non-dairy cattle, sheep	-12% CH ₄ (Mohankumar Sajeew et al., 2018)
Manure acidification	Dairy/non-dairy cattle, sheep	-74% CH ₄ (O'Neill et al., 2026)
Anaerobic digestion	Dairy/non-dairy cattle, pig, poultry	-29% CH ₄ and -23% N ₂ O (Mohankumar Sajeew et al., 2018)
Methane inhibitors	Dairy/non-dairy cattle	-30% CH ₄ (Hazel et al., 2024)

353 2.4.4 The forest system

354 The forest module represents forest land dynamics, biomass supply chains and carbon
355 storage associated with forest management and wood product use. Forest land is
356 represented through two categories: managed forest land and forest open areas, following
357 the NID definitions in Sections 6.3.2.6 and 6.3.4 (EPA, 2024). In Ireland, all forest lands are
358 managed with harvesting, silvicultural and other management activities occurring within
359 these areas. On the contrary, open areas are forest lands with partial or sparse tree cover,
360 distinct from managed forests.

361 The forest biomass supply chain is modelled based on the COFORD Ireland wood flow
362 (COFORD, 2022). Harvested timber is processed into roundwood, sawmill residues and
363 harvesting residues, which subsequently feed into material and energy systems.



364

365 *Figure 3: Interaction between forest biomass supply chain and biofuels production in TIM-LEAF*

366 2.4.4.1 Forest harvesting

367 The model determines the harvesting level subject to the maximum sustainable harvest
368 potential:

$$369 H_{f,t}^{max} = \theta_{f,t} \cdot S_{for,t} \quad (Eq. 5)$$

370 $H_{f,t}^{max}$ is the maximum harvest, $\theta_{f,t}$ represents the sustainable harvest rate and $S_{for,t}$ is forest
371 land area.

372 Harvest yield parameters are derived from the National Forest Inventory (NFI) using two
373 datasets: mean annual felled volume classified by harvest type, and stocked forest area
374 subject to felling interventions between the third and fourth inventory cycles (2017–2022)
375 (DAFM, 2023b, 2024d).

376 The two datasets are reported on different temporal bases: felled volumes are expressed as
377 mean annual values, whereas intervention areas are reported as totals over the five-year
378 inventory interval. To harmonise these datasets, intervention areas are converted to mean
379 annual values prior to yield calculation. Moreover, thinning is represented as a single
380 aggregated management process, with yields averaged across first, second, and
381 subsequent thinning operations to obtain a representative national mean value. Aggregation
382 of thinning types assumes that differences in thinning intensity across stand development



383 stages are adequately captured by a single average value and does not respond
384 dynamically to changes in forest age, species growth or climate.

385 **2.4.4.2 Forest system assumptions**

386 • **Future projections**

387 Historical roundwood data for 2015–2023 are sourced from Forest Statistics 2025, Table 29
388 (DAFM, 2025). From 2024 onwards, harvest levels are projected using a linear extrapolation
389 to 2070. This defines the High Harvest (HH) pathway, representing the upper bound of
390 sustainable roundwood extraction within the modelling framework. Two additional harvest
391 variants are derived from the HH pathway: Medium Harvest (MH): 70% of the HH level and
392 Low Harvest (LH): 40% of the HH level. The MH pathway is applied in the baseline scenario.

393 • **Afforestation pathways**

394 TIM-LEAF allows for future expansion of forest area through afforestation, including the
395 conversion of other land types (wetland, grassland) to managed forest. These options are
396 scenario-specific and can be adjusted to explore policy intervention, carbon sequestration
397 potential, or bioenergy feedstock availability. Historical afforestation rates (2000–2024) show
398 a strong decline from approximately 15,700 ha yr⁻¹ to 1,573 ha yr⁻¹ (DAFM, 2025). A
399 declining exponential function is used to represent the baseline afforestation trajectory. In
400 addition to the baseline pathway, three afforestation scenarios are defined to represent
401 alternative policy ambition levels (Table 6).

402 Table 6: Baseline afforestation levels (hectares per year)

Afforestation pathway	Annual afforestation target	Multiple of 2024 afforestation level (1500 ha)
Low afforestation (LA)	8,000	5.3×
Medium afforestation (MA)	10,650	7.1×
High afforestation (HA)	25,000	16.7×

403 Note: Multiples are calculated relative to the estimated 2024 afforestation level

404 • **User constraints**

405 Based on National Forest Inventory (NFI) data from the last four inventory cycles, thinning
406 and clear-fell interventions are assumed to contribute approximately 75% and 25% of total
407 harvested volume, respectively in the core scenarios. The harvest levels and distribution
408 across felling practices serve as user constraints (activity bounds) in the model ensuring that
409 total forest harvesting does not exceed the sustainable limits of the national forest estate.



410 The maximum potential and 75/25 ratio can be adjusted in scenario files to explore more
411 intensive harvesting or alternative forest policy pathways and their system wide impacts.

412 Table 7: Summary of input values and assumptions for the forestry module

Parameter	Value / Assumption	Units	Source
Harvest yield – thinning	104.4	m ³ /ha	Chapter 8 of the NFI results data 2022 (DAFM, 2023b)
Harvest yield – clear fell	492.5	m ³ /ha	
Thinning vs clear fell share	75 / 25	%	Average NFI Results data for 2006, 2012, 2017, 2022 (DAFM, 2023b, 2024b, 2024d, 2024c)

413 Note: the input values are fixed in the core scenarios across the modelling horizon.

414 2.4.5 Bioenergy supply

415 Bioenergy supply in TIM-LEAF represents the integration of biomass flows from agricultural,
416 forestry and waste systems into the energy sector. Biomass resources are grouped into
417 three categories: agricultural residues and energy crops, forestry-derived biomass and
418 waste-based feedstocks. Each category differs in its representation, with supply either
419 determined endogenously through land-use and harvest decisions, or exogenously through
420 supply curves.

421 Agricultural biomass resources include dedicated energy crops (willow and miscanthus),
422 crop-based residues (wheat and oilseed rape), grass biomass, and livestock manure.
423 Energy crops compete for cropland / grassland within the land-use module, while manure
424 streams are linked to agricultural production levels.

425 Forestry-derived biomass includes forest thinning, sawmill residues and post-consumer
426 recycled wood (PCRW). Forest biomass supply is jointly determined by harvest intensity and
427 forest area dynamics.

428 The model includes other biomass resources from waste and industrial streams, including
429 biodegradable municipal solid waste (BMSW), industrial food waste, tallow and recovered
430 vegetable oil (RVO). These resources are not explicitly modelled within the land-use or
431 forestry systems and are therefore represented exogenously using the Sustainable Energy
432 Authority of Ireland (SEAI) bioenergy supply curve (SEAI, 2022).



433 Table 8: Biomass feedstocks represented in TIM-LEAF

Biomass category	Feedstock	Source in TIM-LEAF	Representation
Forestry residues	Forest thinning	Forest biomass supply chain	Endogenous
	Sawmill residues		
	Post recycled consumer wood (PCRW)		
Energy crops	Willow	Cropland	Endogenous
	Miscanthus		
Agricultural crops	Grass	Grassland	Endogenous
	Wheat	Cropland	
	Oil seed rape		
Livestock residues	Cattle manure	Livestock production	Endogenous
	Pig manure		
Waste biomass	Biodegradable municipal solid waste	Waste stream	Exogenous
	Industrial food waste	Industrial waste stream	
Industrial residues	Tallow	Industrial by product	Exogenous
	Recovered vegetable oil		

434 2.4.5.1 Bioenergy supply potential

435 The total endogenous bioenergy supply available to the energy system is constrained by
436 biomass availability from both agricultural land and forest systems. Supply is represented as:

$$437 \quad ACT_t^{bio} \leq \eta^{conv} \left(\sum_{a \in A_{energy}} \sum_{m \in M} Y_{a,t} \cdot L_{energy,m,t} + \sum_{f \in F} H_{f,t}^{max} \right) \quad (Eq.6)$$

438 ACT_t^{bio} is the endogenous bioenergy consumption determined by the energy system
439 optimisation. $Y_{a,t}$ is the biomass yield per hectare for energy crop a . $L_{energy,m,t}$ is the land
440 allocated to energy crops on land type m and η^{conv} is the biomass-to-energy conversion
441 efficiency.

442 2.4.6 GHG accounting

443 TIM-LEAF accounts for GHG emissions and removals across both the energy system and
444 the AFOLU sector, including CO₂, CH₄ and N₂O. This integrated accounting framework
445 ensures that emissions from energy use, agricultural production and land-use dynamics are
446 consistently represented within a unified carbon balance.



447 $Cumulative\ emissions = E_t^{energy} + E_t^{AFOLU} - \Delta C_t^{Land} + HWP_{Instant\ emissions} - CDR_t$ (Eq. 7)

448 defines the total net emissions in each period and must satisfy the cumulative constraint:

454
$$\sum_{t \in T} Net_t \leq CB$$

449 where E_t^{energy} represents CO₂ emissions from fossil fuel combustion and industrial
450 processes in the energy system, E_t^{AFOLU} includes CO₂, CH₄ and N₂O emissions from
451 agricultural and land-use activities, ΔC_t^{Land} captures carbon stock changes in biomass and
452 soils, $HWP_{Instant\ emissions}$ represents instant carbon losses from harvested wood products at
453 harvest and CDR_t is CO₂ removal from CCS and DACCS technologies.

455
456 HWP immediate harvest emissions and yearly carbon stock are endogenous in TIM-LEAF.
457 However, the annual change in HWP carbon stock is calculated ex post from the modelled
458 HWP stock trajectory and therefore not included within the CB during optimisation.

459 For the GHG accounting results presented in this study, the net emissions reported include
460 the HWP sink, calculated from the difference in annual HWP carbon stocks.

461 2.4.6.1 Energy and agricultural activities emissions

462 Energy-related emissions (CO₂ flows) arise from fuel combustion and industrial processes
463 within the energy system module, linked to activities of energy supply, conversion and end-
464 use technologies ([Section 2.4.1](#)).

465 Agricultural emissions include CH₄ and N₂O fluxes associated with livestock and crop
466 production ([Section 2.4.3](#)). CH₄ emissions from enteric fermentation and manure
467 management are derived from the NID. Nitrous oxide emissions are represented using the
468 FAO emissions database classification, which distinguishes between manure management,
469 manure left on pasture, and manure applied to soils. This allows for a transparent allocation
470 of emissions within the model structure.



471 Table 9: Summary of energy and agricultural emissions in TIM-LEAF

Sector	Process	Emission (gas)	Source	Notes
Energy	-	CO ₂	Fuel consumption / industrial processes	As defined in TIM
Livestock	Animal rearing	CH ₄	Enteric fermentation	NID for CH ₄ , FAO for N ₂ O emissions
		CH ₄ , N ₂ O	Manure management	
	Pasture systems	N ₂ O	Manure left on pasture	FAO database
Tillage		CH ₄ , N ₂ O	Burning crop residues	
		N ₂ O	Crop residues	

472 2.4.6.2 LULUCF emissions

473 LULUCF emissions and removals are represented according to the categories reported in

474 Table 6.2 of the NID (EPA, 2024). TIM-LEAF accounts for CO₂, CH₄, and N₂O sources

475 where applicable.

476 Table 10: LULUCF emissions / removal represented in TIM-LEAF

NID tables reference	Emission source	Emission (gas)	Land type / Source
CRT Tables 4.A to 4. D	Carbon stock changes for living biomass, dead wood, litter and soils	CO ₂ , CH ₄ , N ₂ O	Forest land, cropland, grassland and wetland
CRT Table 4(II)	Drainage and rewetting and other management of organic and mineral soils	CH ₄ , N ₂ O	Forest land
		CO ₂ , CH ₄ , N ₂ O	Grassland, wetland
CRT Table 4(III)	From nitrogen mineralisation/immobilisation	N ₂ O	Grassland
CRT Table 4. G	HWP	CO ₂	Instant harvest emissions and carbon stored

477 2.4.6.3 Carbon accounting

478 Because TIM-LEAF represents both emissions and removals, carbon flows across LULUCF

479 must be explicitly accounted for. This includes carbon stock changes, forest carbon

480 saturation and HWP storage:



481 ▪ **Carbon stock changes**

482 Carbon stock changes are calculated using the Gain–Loss method following the IPCC 2006
483 Guidelines (Aalde et al., 2006). NID implied emission factors (IEF) are applied to all relevant
484 pools: living biomass, dead organic matter (litter and coarse woody debris), and soil organic
485 carbon. Soil carbon is averaged across total soil area due to the lack of disaggregation
486 between mineral and organic soils in the model.

487 To ensure consistent carbon accounting within TIM-LEAF, carbon stock changes are
488 calculated at the managed land-type level rather than separately for land remaining in a
489 land-use category and land converted to that category. In the TIM-LEAF land accounting
490 structure, the managed land area for each land-use type is determined as the sum of land
491 remaining in that category and land converted into it, minus land converted out to other land-
492 use types. Applying IEFs separately to both the "remaining" and "converted" land processes
493 would therefore result in double counting. Estimating carbon stock changes at the managed
494 land-type level avoids this duplication while being consistent with the land balance.

495 In addition, the forest sector has 30-year transition period of land converted to forest before
496 being classified as "forest remaining forest land" (EPA, 2024). Representing this transition
497 within the forest vintage-based structure of TIM-LEAF would incorrectly reset forest age
498 profiles. Accounting for carbon stock changes at the total managed forest level also avoids
499 this distortion of forest age.

500 • **Forest carbon saturation**

501 Forest carbon dynamics are modelled as a function of stand age to capture the temporal
502 evolution of carbon sequestration and the effects of carbon saturation. Each hectare of
503 forest, whether existing in the base year or newly established, is assigned a vintage year
504 representing stand age. Carbon uptake in each period depends on the time elapsed since
505 this vintage year, reflecting forest growth stage.

506 The sequestration profile follows the Chapman–Richards functional form, a growth model
507 widely used in forestry literature (Liu & El-Kassaby, 2018; Ma et al., 2024; Zhao-gang &
508 Feng-ri, 2003)

509
$$S_{(a)} = ka^pe^{-ca}$$

510 Where, a : stand age in years, k : scaling constant controlling maximum rate, p : slope
511 parameter shaping early growth, c : decay constant controlling post peak decline



512 Different p values control early growth shapes: $p < 1$: delayed initial rise, $p = 1$: linear early
513 rise and $p > 1$: sharper, delayed rise before peak.

514 For simplicity, p is assumed to be 1, producing near-linear early growth, a peak at maturity,
515 and gradual decline thereafter. Peak sequestration occurs at age a_{peak} :

516
$$\frac{dS}{da} = 0 \Rightarrow c = \frac{1}{a_{peak}}$$

517 The scaling parameter is defined such that maximum sequestration S_{max} occurs at age
518 a_{peak} :

519
$$S_{max} = k a_{peak} e^{-1} \Rightarrow k = \frac{S_{max} e}{a_{peak}}$$

520 Resulting in the final age-dependent sequestration function:

521
$$S(a) = S_{max} \left(\frac{a}{a_{peak}} \right) e^{\left(1 - \frac{a}{a_{peak}} \right)} \quad (Eq. 8)$$

522 In the absence of age-cohort and forest species tracking in the model, the assumptions are:
523 the current forest stand age for the Irish forest estate is 30 years, according to the last three
524 Annual Forest Statistics approximately 70% of forests consisting of trees 30 years old or
525 younger (DAFM, 2023a, 2024a, 2025). Peak carbon sequestration is assumed to occur
526 between 30 and 35 years, with a maximum rate of 2.52 MtCO₂e yr⁻¹, consistent with the
527 national inventory average of MtCO₂e yr⁻¹ between 1990 and 2023.

528 Table 11: Input parameters for forest carbon saturation profile

Component	Parameter	Value / Assumption	Source	Notes
Forest carbon	Growth model	Chapman–Richards forestry equation		Derive simple growth curve
	Slope parameter, p	1	Own assumption	Produces near linear early growth
	Peak age, a_{peak}	30	Annual forest statistics	-
	Maximum sequestration, S_{max}	2.52 MtCO ₂ e yr ⁻¹	National inventory average	-

529



530 • **HWP carbon stock change**

531 Harvested Wood Products (HWPs) are represented as a carbon storage pool, following the
532 IPCC 2019 Refinement—Tier 1, First-Order Decay (FOD), production approach (Rüter et al.,
533 2019):

534 **i. HWP storage initialisation**

535 The FOD model is path dependent, meaning that carbon stocks in any given year depend on
536 historical inflows. Historical HWP production is therefore reconstructed to initialise the
537 carbon stock at the beginning of the model horizon, using Equations 12.1, 12.3, 12.4, and
538 12.8 of the IPCC 2019 Guidelines (Rüter et al., 2019). In TIM-LEAF, annual HWP inflows are
539 computed for the period 1990–2017 to determine the cumulative initial HWP carbon stock.

540 For each feedstock category R and year i , domestic harvest inflows are corrected for imports
541 and exports (IPCC Equation 12.8).

$$542 \quad f_R(i) = \frac{P_R(i) - EX_R(i)}{P_R(i) + IM_R(i) - EX_R(i)}$$

543 For a specific feedstock category R and year i : $P_R(i)$ is Domestic production, $IM_R(i)$ is
544 Imports and $EX_R(i)$ is Exports.

545 Carbon inflow to HWPs for commodity class l in year i is computed (IPCC Eq. 12.3).

$$546 \quad \text{Inflow}_l(i) = HWP_{P_l}(i) \times f_R(i) \times cf_l$$

547 $HWP_{P_l}(i)$ is the total national production of semi-finished HWP commodity l , cf_l is the carbon
548 conversion factor, and $f_R(i)$ is the feedstock factor, calculated with Equation 12.8.

549 Carbon stocks evolve according to IPCC Equation 12.1.

$$550 \quad C_l(i+1) = C_l(i) e^{-k_l} + \frac{\text{Inflow}_l(i)}{k_l} (1 - e^{-k_l}), \quad \Delta C_l(i) = C_l(i+1) - C_l(i)$$

551 $C_l(i)$ is carbon stock at start of year i , $\text{Inflow}_l(i)$ is carbon entering the pool in year i , $k_l =$
552 $\ln 2 / HL_l$: Decay constant (yr^{-1}) derived from half-life, $\Delta C_l(i)$ is the annual carbon stock
553 change

554 Initial stocks use a 5-year average inflow (1990–1994), IPCC Equation 12.4.



$$C_l(t_0) = \frac{\text{Inflow}_l}{k_l}, \text{Inflow}_l = \frac{1}{5} \sum_{i=t_0}^{t_0+4} \text{Inflow}_l(i)$$

ii. HWP implementation in TIM-LEAF

For computational efficiency, sawn wood and wood-based panels are combined into a single pool (Wood_Products) with a weighted decay constant:

$$k_{\text{eff}} = \frac{\sum_l k_l \cdot \text{Inflow}_l}{\sum_l \text{Inflow}_l}$$

Where, Inflow_l is the 5-year average inflow (1990–1994) for sawn wood and wood based panels in tonnes of carbon (tC) and k_l the individual decay constant. For the Irish HWP pool,

Commodity	Half-life (yr)	k_l	Average inflow (tC, 1990–1994)
Sawn wood	35	0.019804	131659.73
Panels	25	0.027726	60615.29

$$k_{\text{eff}} = 0.0223 \text{ (effective half-life } \approx 31 \text{ years)}$$

The aggregated FOD model becomes:

$$C_{\text{total}}(i+1) = C_{\text{total}}(i)e^{-k_{\text{eff}}} + \frac{\text{Inflow}_{\text{total}}(i)}{k_{\text{eff}}}(1 - e^{-k_{\text{eff}}}) \quad (\text{Eq. 9})$$

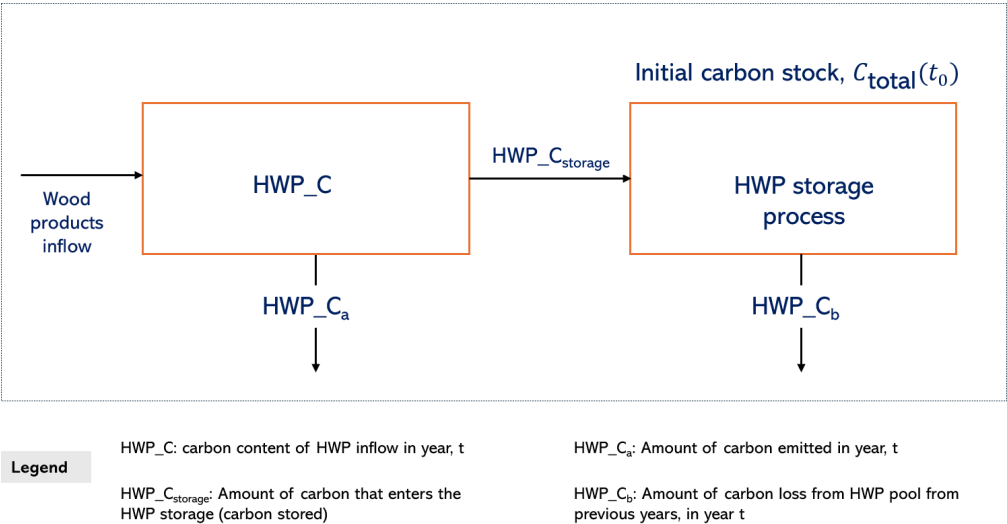
$$\Delta C_{\text{total}}(i) = C_{\text{total}}(i+1) - C_{\text{total}}(i)$$

$\text{Inflow}_{\text{total}}$ is $\text{Inflow}_{\text{sawn wood}} + \text{Inflow}_{\text{wood based panels}}$. Initial stocks for the combined pool follow the 1990–1994 5-year average, in accordance with IPCC Eq. 12.4.

To implement the FOD formulation within TIM-LEAF, it is decomposed into two components: a process flow representation of carbon inflow and a storage-based representation of carbon decay (as illustrated in Figure 4). Carbon from wood products is represented using a process flow efficiency, $\eta_{\text{inflow}} = \frac{1 - e^{-k_{\text{eff}}}}{k_{\text{eff}}}$, which accounts for immediate harvest emissions (HWP_C_a) and carbon inflow (HWP_C_{storage}) transferred to the HWP pool. The second component captures the gradual decay of carbon stored in HWPs over time, $e^{-k_{\text{eff}}}$. Within the storage process, STG_CHRG defines the initial carbon stock, set to $C_{\text{total}}(t_0)$, derived from reconstructed historical stocks while STG_LOSS represents the decay rate, k_{eff} .



577 The HWP carbon stock is an endogenous model output, with annual stock levels determined
578 by the endogenous HWP carbon inflows and the decay of stored carbon. As highlighted in
579 [Section 2.4.6](#), the annual change in HWP carbon stock is, however, calculated ex post from
580 the modelled carbon stock trajectory and represents the potential HWP carbon sink.



581 *Figure 4: Harvested wood products representation in TIM-LEAF*



582 Table 12: Inputs for HWP carbon dynamics accounting

Component	Parameter	Value / Assumption	Source	Notes
HWP Carbon	Feedstock correction, $f_{R(i)}$	IPCC Eq. 12.8	(Rüter et al., 2019)	From 2018 onwards, the correction factor for industrial roundwood is maintained at the 2018 level (according to NID , 2024), Negligible domestic pulp feedstock, $f_{pulp} = 0$
	Domestic harvest	IPCC Eq. 12.7	(Rüter et al., 2019)	-
	Carbon conversion factor	0.25 tC/m ³ for solid wood	EPA (2024)	-
	Half life	Sawn wood (35 years) Wood based panels (25 years)	EPA (2024)	-
	Activity data – Industrial roundwood and wood pulp	Production, imports and exports (1961 to 2024)	FAOSTAT (2025)	Used for feedstock correction
	Activity data – sawn wood and wood based panels	Production (1961 to 2024)	FAOSTAT (2025)	Used for inflow calculation
HWP in TIM-LEAF	WOOD_Products	Sawn wood + wood based panels	Model design	
	Weighted decay constant, k_{eff}	0.0223	Calculated	Based on 1990 – 1994 inflow average

583 2.5 Climate outcomes: temperature response

584 To assess the temperature contribution of the GHGs (e.g. CO₂, N₂O and CH₄) that make up
585 a national mitigation pathway, it is necessary to incorporate a SCM as an extension of the
586 core modelling framework. FaIR v2.1.3 (Leach et al., 2021; Smith, 2023, 2024a) has been
587 incorporated as a module in the TIM-LEAF framework. FaIR v2.1.3 is a set of six equations
588 that simulates the global mean climate system response to GHG and aerosol emissions (see
589 Figure 5; Leach et al 2021).

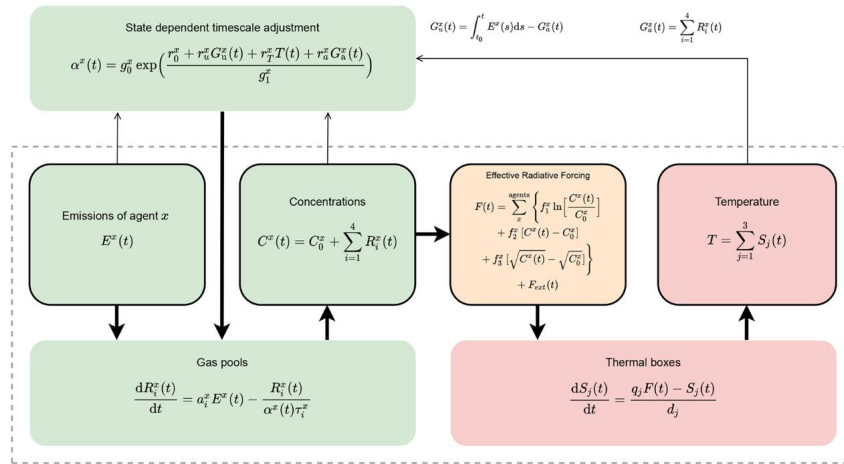


Figure 5: Schematic showing the FaIR v2.0.0 model structure and equations. The model is split into gas cycle (green), radiative forcing (orange) and temperature response components (pink). See Leach et al. (2021) for a full description. Source: Figure 5 reproduced from Leach et al. (2021).

The approach of the Climate Change Commission (CCC) in New Zealand was replicated to assess the warming impact of national mitigation pathways (Climate Change Commission, 2024b, 2024a; Nicholls & Lewis, 2021; Smith, 2024b; Smith et al., 2021). This approach uses a modified locally compiled version of the FaIR v2.1.3 (fair.py) source code so that global baseline emissions scenarios can represent a country level contribution, in this case Ireland's contribution (Climate Change Commission, 2024b).

The modified fair.py has two additional functions (i.e. `def fill_scenarios_from_rcmip(self, RCMIPscenario)` and `def fill_scenario_from_rcmip(self, scenario, RCMIPscenario)`), otherwise it is the same as the original. The first function fills all scenarios that FaIR will run with the same global reduced complexity model intercomparison project (RCMIP) emissions scenario, in this case Shared Socioeconomic Pathway (SSP) 1-2.6. The second function fills a specified FaIR scenario with a given emissions scenario. The Python script used to run this analysis for Ireland (countrylevel_IRL.py), based on a Jupyter Notebook script from the CCC (Climate Change Commission, 2024a, 2024b), uses the first function and then subtracts the values of Ireland's emissions (e.g. CO₂, N₂O and CH₄) from global emissions. This allows 1) the warming that would have happened without Ireland's emissions and 2) the difference between the global baseline and the global baseline without Ireland's emissions, which can be interpreted as the warming caused by Ireland's emissions', to be calculated (Climate Change Commission, 2024b).



612 2.5.1 TIM-LEAF connection to FaIR

613 A fully automated Python-based data pipeline was developed, linking TIM-LEAF to the FaIR
614 model. The workflow starts from TIM-LEAF outputs which are read and parsed into
615 structured data frames using Python. A series of preprocessing functions are then applied to
616 filter relevant processes, parameters and to perform the necessary transformations,
617 including aggregation, unit conversion, and mapping to emissions categories required by
618 FaIR. The resulting dataset is formatted in a CSV file with the required column structure for
619 FaIR input. This dataset is then supplied to the FaIR model (implemented in Python),
620 enabling the full workflow—from TIM-LEAF output to FaIR projections—to be executed in a
621 single automated run without manual data preparation.

622 2.5.2 Data sources and assumptions

623 For the global scenario, SSP1-2.6 was used (Nicholls & Lewis, 2021; R. J. Nicholls et al.,
624 2020). Historical emissions data for Ireland 1750 to 2019 came from Wheatley (2021). This
625 dataset covers GHG and aerosol emissions including fossil CO₂, land CO₂, CH₄, N₂O and
626 sulphur dioxide (SO₂) as described in Wheatley (2023) which also includes the methodology
627 used to construct the dataset. This analysis used emissions of fossil CO₂, land CO₂, CH₄ and
628 N₂O.

629 From 2020 onwards, emissions pathways for Ireland are generated endogenously within the
630 TIM-LEAF model and used as direct inputs to the FaIR. The emissions included in the
631 analysis are energy-related CO₂ emissions, from fossil fuel combustion in the energy
632 system, biogenic CO₂ fluxes from LULUCF, including both emissions and removals and
633 carbon storage in HWP, biogenic CH₄ emissions from agriculture and LULUCF and N₂O
634 emissions from agriculture and land use.

635 3 Model diagnostic scenarios

636 The scenarios presented in this study are illustrative and are not intended to represent policy
637 relevance or optimal national transition pathways. Instead, they are designed as diagnostic
638 experiments to explore how different mitigation levers influence cross-sector interactions and
639 system restructuring under an economy-wide carbon budget constraint.

640 The analysis includes a reference scenario (BAU) and three mitigation scenarios (S1–S3),
641 which vary in terms of bioenergy land availability, afforestation rates and methane abatement
642 measures, as detailed in Table 13.

643 Bioenergy supply is determined by available land for energy crops combined with harvest
644 assumptions based on historical trends. A high harvest (HH) assumption, corresponding to



645 approximately 11 million m³ by 2070, is applied in S1, while reduced harvest potentials are
646 assumed in BAU, S2 and S3 to reflect lower biomass availability under land constraints.
647 Afforestation rates differ across scenarios, ranging from declining historical trends in BAU
648 to progressively increasing annual afforestation in S1–S3. Methane abatement is introduced
649 only in S3 through livestock herd size reductions.

650 All mitigation scenarios are constrained by a cumulative economy-wide carbon budget (CB)
651 of 450 Mt over the period 2021–2050. This budget is used as a diagnostic constraint for
652 scenario comparison and is broadly consistent with the cumulative scale of Ireland’s CB1
653 (2021–2025) and CB2 (2026–2030). The 450Mt CB is applied as a constraint on total GHG
654 emissions which includes both energy-related emissions and AFOLU emissions, defined in
655 the methodological section.



656 Table 13: Scenario protocol

Scenario	Land for bioenergy	Afforestation	CH ₄ abatement	Narrative
BAU	Upper bound (UB) 15,000 ha by 2070 of land for energy crops + 70% of High Harvest (HH)* (as per current trends)	Declining as per historical pattern	-	Reference case with no constrained carbon budget (CB)
S1	UB of 300,000 ha + HH	8,000 ha per year	-	Biomass-intensive mitigation pathway prioritising high land allocation to domestic bioenergy and forest biomass extraction. It is used test the role of large-scale biomass availability in substituting for electrification and other renewable energy (RE) deployment under a CB
S2	UB of 150,000 ha + 70% of HH	10,600 ha per year	-	A balanced pathway with reduced biomass avail ability relative to S1 and mitigation is distributed across afforestation, afforestation and RE expansion
S3	UB of 50,000 ha + 40% of HH	25,000 ha per year	Herd size reduction of dairy and non- dairy cattle (50% decrease relative to year 2022 by 2050)	A structural transformation pathway in which reduced agricultural demand and methane mitigation reduce pressure on land resources, allowing large scale afforestation and ecosystem restoration. It explores an alternative mitigation configuration in which reductions in agricultural sector substitute for extensive bioenergy development

657 *High harvest (HH) = Forest harvest projections based on historical pattern (~11 million m³ by 2070).

658 Upper bounds for land are all by 2070.



659 3.1 Integrated analysis outcomes

660 Figure 6 presents the integrated response of the TIM-LEAF system across the four
661 diagnostic scenarios. The matrix illustrates how alternative assumptions regarding biomass
662 availability, afforestation and agricultural methane abatement influence (i) the evolution of
663 the primary energy system, (ii) land allocation, (iii) GHG emissions and (iv) climate
664 outcomes.

665 i. Total primary energy demand

666 The main difference in the primary energy demand lies in the contribution of bioenergy within
667 the energy mix (Figure 6, Row (a)). Under the biomass-intensive mitigation pathway (S1),
668 where both energy crop deployment and forest harvesting are maximised, bioenergy uses
669 increase from 33.8 PJ in 2020 to over 105 PJ by 2070, supplying approximately 16% of total
670 primary energy demand (PED). Reducing biomass availability in S2 limits bioenergy
671 deployment to around 65 PJ (10% of PED), while S3 further reduces bioenergy use to 43.8
672 PJ (7%).

673 The lower contribution of bioenergy in S3 is a direct consequence of the land-use
674 assumptions. Although land allocated to energy crops increases substantially relative to the
675 BAU case (33.8 kha compared with 7.5 kha by 2070), this increase is outweighed by a
676 reduction in forest biomass availability resulting from lower harvest assumptions. As a result,
677 total land-dependent biomass resources (forest biomass and energy crops) decline from
678 approximately 39 PJ in BAU to 27.5 PJ in S3.

679 The energy system partially compensates by increasing the utilisation of biomass feedstocks
680 that are independent of land availability, including municipal solid waste, industrial residues,
681 tallow and waste oils. These secondary biomass resources increase from 12.5 PJ in BAU to
682 16.3 PJ in S3 by 2070. Nevertheless, total primary biomass availability declines from
683 approximately 51.5 PJ (BAU) to 43.8 PJ (S3), limiting the overall role of bioenergy in the
684 energy system.

685 Additionally, differences in total PED between the BAU and mitigation scenarios are
686 relatively modest. This reflects a BAU scenario, which already incorporates existing and
687 expected energy-sector decarbonisation. The scenarios are intended as diagnostic
688 comparisons that isolate the influence of alternative land-use and biomass assumptions
689 under a common modelling framework. Future work will consider a revised BAU scenario
690 that provides greater contrast with the mitigation pathways.



691 **ii. Land allocation**

692 Land allocation evolves differently across the scenarios in response to competing demands
693 for agricultural production, bioenergy deployment and afforestation (Figure 6, Row (b)).

694 Within the model, land classified as "Other" represents cropland and grassland that are not
695 allocated to any productive use, it acts as a reserve of agricultural land available for
696 reallocation. Expansion of both energy crops and forest land occurs through conversion of
697 this available land.

698 In S1, the mitigation strategy prioritises domestic biomass production alongside
699 afforestation. Land allocated to energy crops, expand from 0.01 Mha in 2020 to 0.21 Mha by
700 2070, while forest land increases from 0.79 Mha to 1.14 Mha. Under the more constrained
701 biomass assumptions in S2, energy crop deployment is reduced to 0.06 Mha by 2070, while
702 forest area increases to 1.25 Mha.

703 The most pronounced land-use restructuring occurs in S3. Livestock herd reductions
704 substantially reduce pasture requirements, with pasture area declining from 3.59 Mha in
705 2020 to 2.26 Mha by 2070. This releases additional agricultural land into the "Other"
706 category, creating a larger pool of land available for reallocation. The model allocates this
707 land to afforestation, increasing forest area to 1.87 Mha by 2070, while a relatively small
708 proportion is used for energy crops (0.03 Mha). This suggesting that CH₄ mitigation
709 measures may create additional opportunities for ecosystem restoration and non-productive
710 land uses.

711 Additionally, analysis of land conversion pathways under the 450 Mt carbon budget indicate
712 that the model preferentially preserves existing forest land while expanding forest area
713 where additional mitigation is required. To minimise additional LULUCF emissions
714 associated with land conversion, forest expansion occurs primarily through limited
715 conversion of grassland and wetland areas. In contrast, forest land converted into other
716 land-use categories shows little transition over the modelling horizon.

717 The land allocation results show how the integrated framework endogenously prioritises
718 land-use configurations that minimise cumulative LULUCF emissions while simultaneously
719 meeting land demands for bioenergy production, afforestation and agricultural activity.

720 **iii. Total system GHG emissions**

721 The diagnostic scenarios show the combined effects of fossil fuel substitution, changes in
722 land use, afforestation, and negative emissions technologies for emission reductions and
723 removals within the framework (Figure 6, Row (c)). The reported net GHG emissions include
724 the HWP carbon sink calculated ex post, as described in [Section 2.4.6.](#)



725 In BAU, lower emissions are primarily driven by reductions in energy-sector emissions, while
726 agricultural emissions and land-use emissions remain broadly stable. Land-use change
727 contributes a relatively constant emissions profile, with declining forest sinks partially
728 offsetting increases in land-use emissions over time. As a result, net emissions decrease
729 from 57.5 MtCO₂e in 2020 to 30.7 MtCO₂e in 2070.

730 In S1, the reduction in net emissions is driven primarily by energy system decarbonization
731 and large-scale deployment of BECCS, which becomes the main CDR pathway (up to -6.1
732 MtCO₂e by 2070). The LULUCF sink contributes a further -2.9 MtCO₂e, while HWP storage
733 contributes -2.4 MtCO₂e. As a result, net emissions fall to 12.3 MtCO₂e in 2070.

734 Compared to S1, S2 results in a higher net emission of 19.3 MtCO₂e in 2070. In this
735 scenario, BECCS has a CO₂ removal of around -2.8 MtCO₂e in 2070, while the LULUCF
736 sink increases to -3.2 MtCO₂e, but this additional land-based removal is insufficient to
737 compensate for the lower BECCS contribution.

738 Following a more balanced mitigation portfolio, S3 shows the combined effect of enhanced
739 afforestation, bioenergy and BECCS deployment, herd size reduction and continued
740 decarbonisation of the energy system. The LULUCF sink increases to -5.1 MtCO₂e by 2070,
741 while BECCS contributes -2.1 MtCO₂e. At the same time, agricultural emissions decrease
742 from 18.9 MtCO₂e in 2020 to 11.2 MtCO₂e in 2070. These combined mitigation measures
743 lead to the lowest net emissions of the three mitigation scenarios, at 10.0 MtCO₂e in 2070.



744 **iv. Temperature response**

745 The resulting temperature responses show the distinct long-term climate outcomes of
746 alternative emissions pathways (Figure 6, Rows (d)). While the baseline pathway exhibits
747 continued warming till 2100, the mitigation scenarios show progressively lower temperature
748 responses with differences in the composition and timing of their respective multi-gas
749 emissions pathways. In S1 and S2, the overall temperature response approaches
750 stabilisation towards the end of the century, while S3 shows a peak-and-decline response
751 around mid-century.

752 In S1, the CO₂ contribution to warming shows a more pronounced decrease due to the
753 higher level of CDR through BECCS in the scenario. In S2 and S3, the CO₂ contribution is
754 closer to stabilisation by end of century.

755 The peak-and-decline behaviour in S3 is a response to the herd size reduction implemented
756 in the scenario, leading to considerable reduction in agricultural CH₄ emissions. This
757 highlights importance of near-term reductions in CH₄ (a short-lived GHG) which can reduce
758 warming.

759 Overall, the results show the value of linking national integrated modelling to climate
760 outcomes, demonstrating how different temperature responses emerge from alternative
761 sectoral emissions pathways. The temperature responses of the scenarios highlight that the
762 climate outcome of a mitigation pathway depends not only on the magnitude of the total
763 GHG emission reductions, but also on the gases being reduced, the sectors in which
764 reductions occur and the timing of these reductions.



Figure 6: Integrated assessment of energy, land-use and climate outcomes across the four diagnostic scenarios (BAU, S1–S3). Scenarios are arranged column wise, with each row showing a different component of the integrated analysis. (a) is the total Primary energy demand (PJ), shown as stacked bars by energy



771 source, with the contribution of bioenergy expressed as a percentage of total primary energy demand on the
772 secondary axis (Black line with red markers). (b) presents land allocation (Mha) by major land category.
773 Energy crops include dedicated bioenergy crops cultivated on both cropland and grassland. Pasture
774 represents grassland allocated to livestock production, while tillage denotes cropland used for food crop
775 production. The Other category represents the combined area of cropland and grassland that is not allocated
776 to productive agricultural uses and constitutes the pool of land available for future reallocation. (c) illustrates
777 total greenhouse gas emissions and removals (MtCO₂e) across the energy and AFOLU sectors, including
778 energy emissions, agricultural emissions, LULUCF emissions and removals, HWP carbon storage and
779 BECCS. HWP annual carbon stock change is calculated ex post and included in the reported net emissions.
780 Net emissions are shown on as solid line with purple markers. (d) presents the warming contribution of CO₂,
781 CH₄ and N₂O (°C; IRL stands for Ireland) estimated using the FaIR simple climate model.



3.2 Marginal Abatement Cost diagnostic scenarios

To assess the robustness of the integrated TIM-LEAF framework, two sets of marginal abatement cost (MAC) diagnostic scenarios were analysed to observe how the availability of additional mitigation options influences the cost of achieving the imposed climate constraint. The first set tests the sensitivity to afforestation availability, while the second tests the sensitivity to bioenergy deployment potential.

These scenarios are purely intended as experiments to test the behaviour of the modelling framework, rather than as policy-relevant emissions pathways. By varying the availability of individual mitigation options while holding other assumptions constant, they assess whether changes in model inputs lead to expected changes in system outcomes and mitigation costs.

For the afforestation scenarios, the annual afforestation rate was varied between a low-afforestation case (8,000 ha yr⁻¹) and a high-afforestation case (25,000 ha yr⁻¹), while bioenergy availability, livestock numbers, and all other assumptions were held constant. For the bioenergy scenarios, the land availability of bioenergy pathways varied between low and high bioenergy cases while maintaining consistent afforestation assumptions, and livestock levels.

Across all four diagnostic scenarios, a relaxed carbon budget was applied, consisting of a cumulative carbon budget of 1150 Mt CO₂e over 2021–2050, followed by a net-zero CO₂ constraint from 2051.

For the MAC analysis, DACCS is modelled differently as a defined process representation with electricity and atmospheric CO₂ as inputs with technology-specific investment and operating costs included. Its deployment represents the requirement for permanent atmospheric CO₂ removal to compensate for residual emissions that cannot be eliminated through available mitigation measures.

3.2.1 MAC results

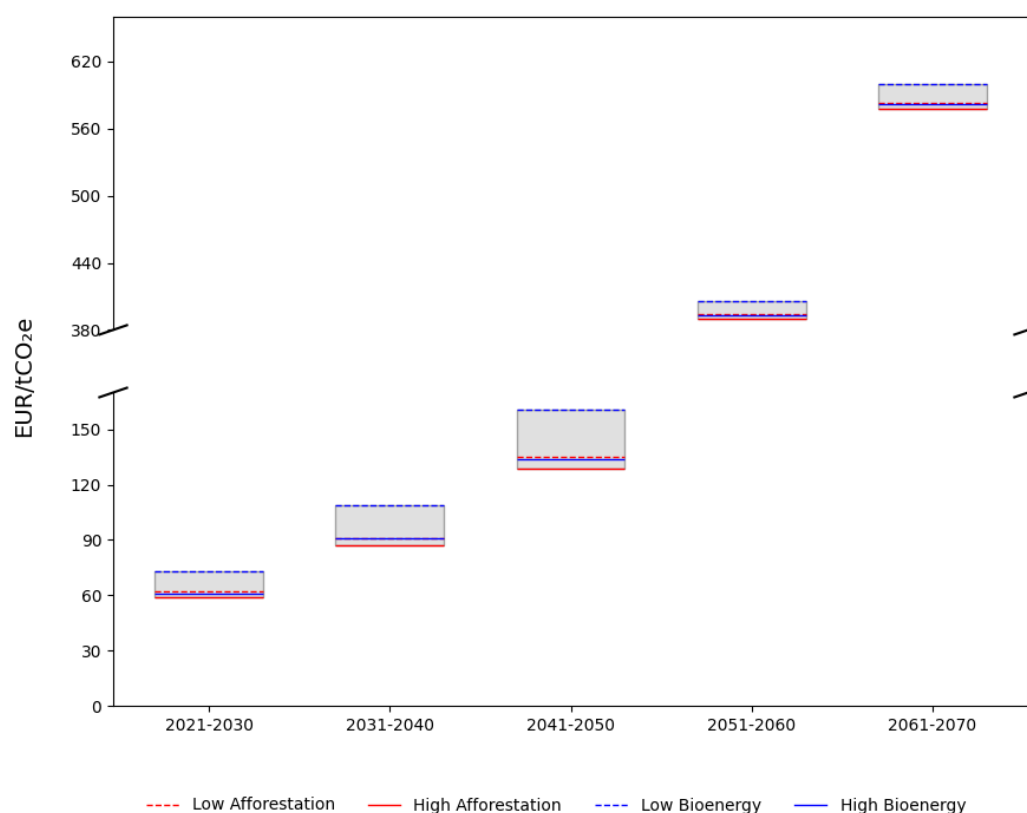
Figure 7 represents the average MAC by decade for the four diagnostic scenarios, providing an indication of the additional system cost required to achieve increasingly stringent emissions reductions.

During the first carbon budget period (2021–2050), MAC values grow steadily across all scenarios, from an average of €64 tCO₂e⁻¹ in 2021–2030 to €140 tCO₂e⁻¹ in 2041–2050. During this period, the model can use the broader portfolio of mitigation options across the energy and LULUCF sectors, allowing emissions reductions through relatively low-cost measures.

With the introduction of the net-zero CO₂ constraint after 2050, lower-cost mitigation opportunities become limited, and DACCS becomes the marginal mitigation option available, resulting in higher marginal abatement costs.



815 The post 2050 MAC results reflects the availability of land-based mitigation options—the high
816 afforestation scenario has the lowest marginal abatement costs, reaching an average of €578
817 $\text{tCO}_2\text{e}^{-1}$ during the 2061–2070 period, compared with €583 $\text{tCO}_2\text{e}^{-1}$ under low afforestation.
818 Similarly, increasing bioenergy availability reduces marginal costs, with the high-bioenergy scenario
819 reaching €582 $\text{tCO}_2\text{e}^{-1}$, compared with €600 $\text{tCO}_2\text{e}^{-1}$ under low bioenergy.



820 *Figure 7. Average marginal abatement cost (MAC) in EUR/tCO₂e by decade for the four scenarios. Box plots*
821 *represent the distribution of annual MAC values within each decade. Red lines indicate the afforestation*
822 *scenarios (solid = high, dashed = low) and blue lines indicate the bioenergy scenarios (solid = high, dashed =*
823 *low). Increasing MAC values reflect the progressive transition from lower-cost mitigation measures towards*
824 *higher-cost engineered carbon removal.*

825 3.2.2 Cumulative emission pathway

826 Figure 8 presents the cumulative CO₂e emissions pathway for the high-bioenergy diagnostic
827 scenario as an illustrative example. Equivalent cumulative emissions pathways for the low-
828 bioenergy, low-afforestation, and high-afforestation scenarios are provided in Appendix B.

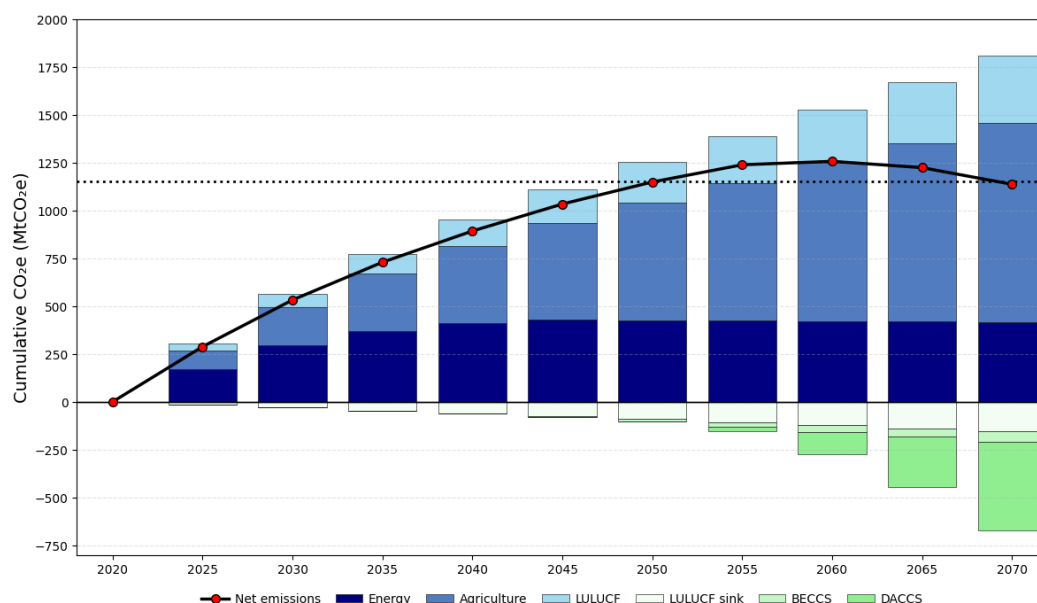


Figure 8. Cumulative CO₂e (in MtCO₂e) emissions pathway for the high-bioenergy diagnostic scenario. Stacked bars represent cumulative sectoral emissions and removals from energy, agriculture, land-use change, biological carbon sinks, BECCS and DACCS) at five year intervals from 2020 to 2070. The black line with red markers represents cumulative net emissions, and the dotted line indicates the 1150 Mt CO₂e carbon budget. The figure illustrates the carbon budget overshoot and the subsequent reduction in cumulative emissions as engineered carbon removal is progressively deployed.

Across all diagnostic scenarios, cumulative emissions approach the 1150 Mt CO₂e carbon budget by 2050. Cumulative emissions reach their maximum around 2060 in all scenarios, after which increasing rates of DACCS deployment reduce cumulative net emissions by 2070.

The magnitude of the overshoot varies according to the availability of mitigation options— the high-afforestation scenario exhibits a maximum overshoot of approximately 105 Mt CO₂e, closely followed by the high-bioenergy scenario (106 Mt CO₂e). In the low-afforestation scenario, there is a maximum overshoot of 104 Mt CO₂e, while the low-bioenergy scenario has the largest overshoot of 157 Mt CO₂e.

These differences are reflected in the cumulative CO₂ removals by DACCS. The high-afforestation scenario requires the lowest cumulative DACCS removals (449 Mt CO₂e by 2070, followed by the high-bioenergy scenario (462 Mt CO₂e), low afforestation (467 Mt CO₂e), and low bioenergy (468 Mt CO₂e).

These diagnostic scenarios demonstrate that land-based mitigation options and engineered carbon removal act as complementary components within TIM-LEAF. Increasing afforestation and



849 bioenergy availability reduces marginal abatement costs and decreases reliance on DACCS.
850 However, even under high-afforestation and high-bioenergy conditions, DACCS remains necessary
851 to achieve the long-term climate constraint because residual agricultural CH₄ emissions persist
852 within the model framework.

853 4 Discussion

854 TIM-LEAF advances national climate mitigation modelling by integrating land, energy, agriculture,
855 forestry and climate dynamics within a single inventory-aligned optimisation framework. While
856 interactions between these systems are widely recognised in the climate literature, they are often
857 represented using separate models, making it difficult to assess trade-offs and synergies
858 consistently within a national decarbonisation context. TIM-LEAF addresses this gap by linking
859 AFOLU processes, CDR options, energy system transformation and climate outcomes through a
860 common framework.

861 At the national level, TIM-LEAF combines multiple modelling features, either absent or partially
862 represented in existing sectoral models, including land allocation, forest dynamics, integrated
863 biomass supply chains, LULUCF carbon stock changes and GHG accounting (Table 14). By filling
864 these gaps, TIM-LEAF enables system wide analysis of emissions pathways that are both
865 physically—through resources, biomass and land—and economically—through least cost
866 optimisation of the energy sector—consistent across sectors, while remaining aligned with national
867 resources, capacities, and constraints.



868 Table 14: Comparison of modelling capabilities across Irish frameworks

Model Capability	FAPRI-Ireland	GOBLIN 1.0	TIM	TIM-LEAF
National energy system optimisation	○	○	●	●
Agricultural production representation	●	●	●	●
Econometric modelling of agricultural market and policies	●	○	○	○
Explicit land allocation & land capacity constraints	○	●	○	●
Spatial land representation	○	○	○	○
Forest dynamics	○	●	○	●
Biomass supply linked to energy system demand and land availability	○	◐	◐	●
Agricultural GHG emissions (CO ₂ , CH ₄ , N ₂ O)	●	●	◐	●
LULUCF carbon stock changes & HWP accounting	○	●	○	●
Exploring land use pathways	○	●	○	●
Integrated systems decarbonization pathways under CB	○	○	◐	●
Temperature response included in framework	○	○	○	●

Legend: ● Fully represented ◐ Partially represented ○ Not represented

869 Notes: GOBLIN 1.0 does not include explicit spatial land representation; however, this functionality is
870 available in the GeoGOBLIN version (Duffy et al., 2024). GOBLIN 1.0 simulates biomass availability based on
871 the modelled land balance but there is no explicit link to energy system demand. TIM represents biomass
872 availability using exogenous SEAI bioenergy supply curves for energy crops, forestry and other biomass
873 feedstocks. TIM-LEAF endogenously links biomass supply to both energy system demand and land
874 availability, while continuing to rely on SEAI supply curves for biomass feedstocks that are not land-driven, as
875 described in the methodology. TIM focuses only on energy-related CO₂ emissions. TIM applies carbon
876 budgets, but the emissions constraint is limited to energy system CO₂ emissions.

877 4.1 Significance and future applications

878 The contribution of TIM-LEAF extends beyond the Irish context. To our knowledge, it is the first
879 national scale TIMES-based model that links energy and AFOLU in a single optimisation framework
880 with carbon accounting consistent with national inventories. TIM-LEAF introduces several
881 methodological advances that are relevant not only for Ireland but also for the development of state-
882 of-the-art national integrated models.

883 TIM-LEAF's integrated structure addresses a key limitation in national ESMs: simplified or
884 exogenous representations of agriculture and forestry (IPCC, 2022a). Such simplification can



885 overlook critical interdependencies between energy, land use, and food systems, as well as the role
886 of agricultural mitigation levers, including deep CH₄ reductions (Price et al., 2023).

887 Another improvement lies in its treatment of land and biomass as system level resources. Major
888 land categories are disaggregated and explicitly allocated across competing uses, subject to
889 capacity constraints, capturing interactions between agriculture, forestry, bioenergy, and energy
890 system decisions. Unlike conventional energy systems, where bioenergy supply is often
891 exogenously assumed, TIM-LEAF links biomass supply directly to land availability and forest
892 dynamics, adding an explicit forest biomass supply chain and land-dependent energy crop
893 production. This allows assessment of realistic land requirements for large-scale bioenergy
894 production (Harper et al., 2018) in national mitigation pathways and resultant trade-offs with other
895 land uses.

896 TIM-LEAF advances national GHG modelling by tracking CO₂, CH₄, and N₂O emissions from major
897 sectors in alignment with the national inventory. Changes in agricultural production, forest
898 management, or land restoration can therefore contribute to the national GHG balance, influencing
899 the level of emissions reductions required from the energy system. This is particularly important for
900 short-lived climate pollutants such as CH₄, where rapid reductions can reduce peak warming, lower
901 reliance on future negative CO₂ emissions and improve air quality (IPCC, 2021; Szopa et al., 2026).

902 In addition, the model improves the representation of bioenergy emissions. Bioenergy is often
903 treated as carbon neutral where emissions from combustion are assumed to be offset by biomass
904 regrowth (Searchinger et al., 2018). In TIM-LEAF, biomass combustion emissions are set to zero,
905 while CO₂ emissions associated with land use are captured through changes in land based carbon
906 stocks. This approach ensures that the carbon emissions associated with biomass use are better
907 accounted for within the model and that the net mitigation value of bioenergy takes more into
908 consideration the underlying land use dynamics from which the biomass resource originates
909 (Christianides et al., 2025).

910 Forest carbon dynamics are driven by changes in carbon sequestration over time, reflecting stand
911 age and the forest lifecycle. TIM-LEAF improves this representation through a practical vintage-
912 based approach. This allows the model to reflect saturation effects, whereby carbon uptake declines
913 as forests mature despite increasing carbon stocks (Huang et al., 2025; Nabuurs et al., 2013; Zhu et
914 al., 2019). As a result, forest carbon sinks can be represented in a manner consistent with national
915 inventory reporting while remaining computationally tractable within an optimisation framework.

916 A further methodological advance is the integration of the FaIR simple climate model is included in
917 the workflow of a national integrated model framework. To our knowledge, this is the first
918 implementation of such a process within a national TIMES-type integrated modelling framework



919 workflow. This extends the analysis beyond emissions to temperature responses. Similar carbon
920 budgets, expressed in cumulative CO₂ equivalence, can result in different temperature responses,
921 depending on the timing and composition of GHG emissions and removals. In particular, differences
922 in the magnitude and timing of CH₄ reductions will result in different temperature outcomes, which
923 has particular significance for the timing and magnitude of peak warming and the level of future
924 CDR needed. Moving beyond CO₂ equivalent or other metrics is important when national climate
925 policy is centred on climate outcomes rather than GHG targets alone.

926 The illustrative scenarios demonstrate that land-use decisions are not confined to the AFOLU
927 sector, rather, they propagate throughout the integrated land, energy and climate system, under a
928 common cumulative carbon budget. Across the scenarios, changes in land use and land conversion
929 alter the availability of biomass feedstocks and forest carbon sequestration, leading to different
930 patterns of primary energy supply, technology deployment and GHG emissions. These changes
931 subsequently affect projected temperature responses through differences in the magnitude and
932 timing of CO₂, CH₄ and N₂O emissions. Collectively, the scenarios highlight the value of integrated
933 systems analysis for identifying and managing cross-sectoral trade-offs and synergies that would be
934 difficult to capture when these systems are analysed in isolation.

935 These advances shift national energy system modelling towards an integrated carbon system
936 perspective. TIM-LEAF enables the assessment of how alternative agricultural and land-use
937 pathways influence emissions trajectories, biomass availability for energy and CDR deployment,
938 and the configuration and cost of the energy system. Land conversion processes, such as
939 reallocating land from livestock production to forestry, can be simulated to evaluate the mitigation
940 implications of land-use transitions. It also enables exploration of mitigation strategies that reduce
941 pressure on land, such as LED pathways, which minimise reliance on large-scale BECCS and
942 associated land requirements (Gidden et al., 2019; Grubler et al., 2018; Riahi et al., 2017; Rogelj et
943 al., 2018). Extending low demand concepts to agriculture can analyse how production transitions
944 and dietary shifts influence land availability, bioenergy deployment and long-term mitigation
945 pathways.

946 Future applications of TIM-LEAF include analysing alternative agricultural transition pathways,
947 dietary shifts, novel food production systems, peatland restoration, biochar deployment and
948 emerging bio-based feedstocks for advanced fuels. The framework also provides a platform for
949 evaluating future carbon budgets, net-zero GHG pathways and national strategies for balancing
950 emissions reductions with carbon removals. More broadly, TIM-LEAF provides a transferable
951 methodological template for countries seeking to assess interactions between energy, land-use and
952 agricultural systems within long-term decarbonisation planning.



953 4.2 Limitations

954 While TIM-LEAF represents a significant advancement, several limitations are important to
955 acknowledge.

956 First, TIM-LEAF model adopts a simplified national-scale representation of the AFOLU sector that
957 does not represent spatially explicit land-uses or land suitability. Linking TIM with a detailed spatial
958 land-use model could introduce additional uncertainty, computational complexity and may reduce
959 transparency and tractability, and increase the difficulty of interpreting model behaviours with
960 diverse knowledge systems (Keppo et al., 2026).

961 Second, agricultural land use and production pathways in TIM-LEAF are exogenously defined rather
962 than optimised endogenously. This reflects the reality that agricultural decision-making is influenced
963 by a range of social, cultural, policy and behavioural factors that are not easily represented through
964 purely economic optimisation. Agricultural profitability in Ireland is relatively low across several
965 production systems, and many farms rely on public support payments or off-farm income (Dillon et
966 al., 2024; OECD, 2026). Moreover, many non-financial constraints to afforestation remain (Lentz et
967 al., 2026). Consequently, a purely cost-optimised representation of the AFOLU sector could produce
968 unrealistic land-use outcomes, particularly when planting and managing forests is incentivised
969 (Forestry Division, 2024). Future work could address this limitation by integrating responses to
970 agricultural prices, policies and land profitability.

971 Third, the forest sector representation remains simplified. National forestry datasets are
972 characterised by forest species with different growth trajectories, size distributions and development
973 stages (DAFM, 2023b, 2025). TIM-LEAF does not capture this heterogeneity explicitly and
974 additionally yields for thinning processes are approximated as single average parameters. This
975 limits stand-level analyses and rotation-specific management assessments, which are better
976 addressed through sectoral modelling approaches. Uncertainties in forest productivity and
977 management could be explored through sensitivity analyses varying yield assumptions, harvest
978 intensity or forest policy scenarios.

979 Fourth, the annual HWP carbon stock change is calculated ex post from the endogenous yearly
980 HWP carbon stock in order to simplify the current model formulation. Including an endogenous
981 annual stock change would require an additional constraint formulation linking HWP carbon flows
982 across model periods, this inclusion is planned for future improvement. Consequently, although
983 HWP stock changes are included in the post-model GHG accounting, they do not currently provide
984 a CDR credit within the carbon-budget constraint during optimisation. Endogenising this HWP stock



985 change in the optimisation framework would allow HWP removals to influence technology and land-
986 use choices and could therefore alter the least-cost mitigation pathway.

987 Fifth, several key drivers of future mitigation pathways remain uncertain. Afforestation rates,
988 agricultural production trajectories, biomass yields, future carbon budgets and technology
989 deployment assumptions all influence model outcomes. While these uncertainties are an inherent
990 feature of forward-looking modelling, they highlight the importance of interpreting scenario results as
991 exploratory pathways rather than forecasts. Future work could investigate these uncertainties
992 through structured sensitivity analysis and scenario ensembles. Furthermore, projected temperature
993 responses depend on assumptions regarding global background emissions and climate system
994 behaviour embedded within FaIR. Although this approach provides a transparent and
995 computationally efficient means of assessing temperature outcomes, it should not be interpreted as
996 a fully coupled climate-economy framework.

997 Finally, TIM-LEAF currently focuses on a limited set of CDR strategies, primarily afforestation,
998 reforestation, BECCS and DACCS. Expanding the portfolio could reduce pressure on land and
999 energy systems and provide additional flexibility in achieving climate targets (Fuhrman et al., 2023).
1000 Future work could incorporate additional CDR strategies such as biochar production or peatland
1001 restoration. Similarly, the model could be used to depict new agricultural mitigation pathways, for
1002 example through novel food proteins, which could further reduce emissions while influencing land-
1003 use dynamics (Kozicka et al., 2023), as well as explicitly depict biogenic carbon from crops,
1004 residues and waste as feedstocks for advanced fuels such as electro-Sustainable Aviation Fuel (e-
1005 SAF).

1006 5 Conclusion

1007 To achieve the goals of the Paris Agreement, the climate challenge needs to be understood as a
1008 whole system problem, rather than a collection of independent sectoral transitions. Interactions
1009 between the energy system, agriculture, forestry and land use increasingly shape the feasibility, cost
1010 and effectiveness of national decarbonisation pathways.

1011 This paper presents TIM-LEAF, a national integrated modelling framework that combines, land,
1012 energy, agriculture and forest systems within a single optimisation structure. The framework is
1013 aligned with the national GHG inventory and further extends a TIMES based model to include a
1014 simple climate model. TIM-LEAF improves national modelling by explicitly representing AFOLU
1015 dynamics, multi-gas accounting and temperature response in a consistent workflow.

1016 The framework demonstrates how interactions between agricultural methane mitigation,
1017 afforestation, forest carbon sequestration, biomass utilisation and energy system transformation



1018 influence national climate pathways. The illustrative scenarios show that pathways achieving similar
1019 cumulative emissions may rely on substantially different mitigation strategies and can produce
1020 different temperature responses depending on the timing and composition of greenhouse gas
1021 emissions. These findings highlight the importance of moving beyond sector-specific analysis and
1022 aggregate CO₂-equivalent metrics when evaluating long-term mitigation strategies.

1023 The model provides a coherent depiction of cross sectoral interactions that would otherwise remain
1024 obscured, allowing users to identify and assess system wide mitigation levers that are beyond the
1025 scope of sector specific analysis. By treating land availability, biomass resources, greenhouse gas
1026 emissions and carbon removals as interconnected components of a national system, increasingly
1027 connected by carbon, TIM-LEAF enables assessment of mitigation opportunities and trade-offs that
1028 are relevant under finite carbon budgets and growing land constraints.

1029 While the framework necessarily involves simplifications in spatial resolution, land-use and
1030 technological detail, these reflect a deliberate balance between tractability, transparency and system
1031 integration. The aim of TIM-LEAF is not to show all sectoral complexity in a single model but rather
1032 be a structured environment where important interactions and trade-offs can be explored.

1033 Overall, TIM-LEAF demonstrates the value of moving beyond siloed sectoral modelling approaches
1034 towards integrated national systems analysis. As countries progress from target setting to
1035 implementation and face increasing land and resource constraints, such national framework can
1036 support a broader assessment of system-wide synergies, trade-offs and climate outcomes in long-
1037 term mitigation planning. The approach presented here offers a transferable template for applying
1038 integrated energy-land modelling to various country contexts.

1039 **Appendix A**

1040 **A.1 Model notation**

1041 **Table A1: List of model sets**

Symbol	Description
$t \in T$	Set of model years
$c \in C$	Set of commodities (energy carriers, land, material)
$k \in K$	Set of technologies or processes
$m \in M$	Set of land types
$a \in A_{AFOLU}$	Set of AFOLU activities including energy crops and land use change
$a \in A_{Energy}$	Set of biomass energy crop activities
$f \in F$	Set of forest management or harvesting activities
$i \in I$	Set of livestock categories
$j \in J$	Set of crop categories



Symbol	Description
$n \in M$	Index representing alternative land types in land-use conversion

1042 **Table A2: List of model parameters**

Parameters	Description
$Y_{a,t}$	Biomass yield per hectare for energy crop a in year t
$H_{f,t}^{max}$	Maximum sustainable forest harvest for forest f in year t
η^{conv}	Biomass-to-energy conversion efficiency
$S_{m,t}$	Physical stock of land type m in year t
$\gamma_{m \rightarrow n}$	Maximum allowable land conversion share from m to n

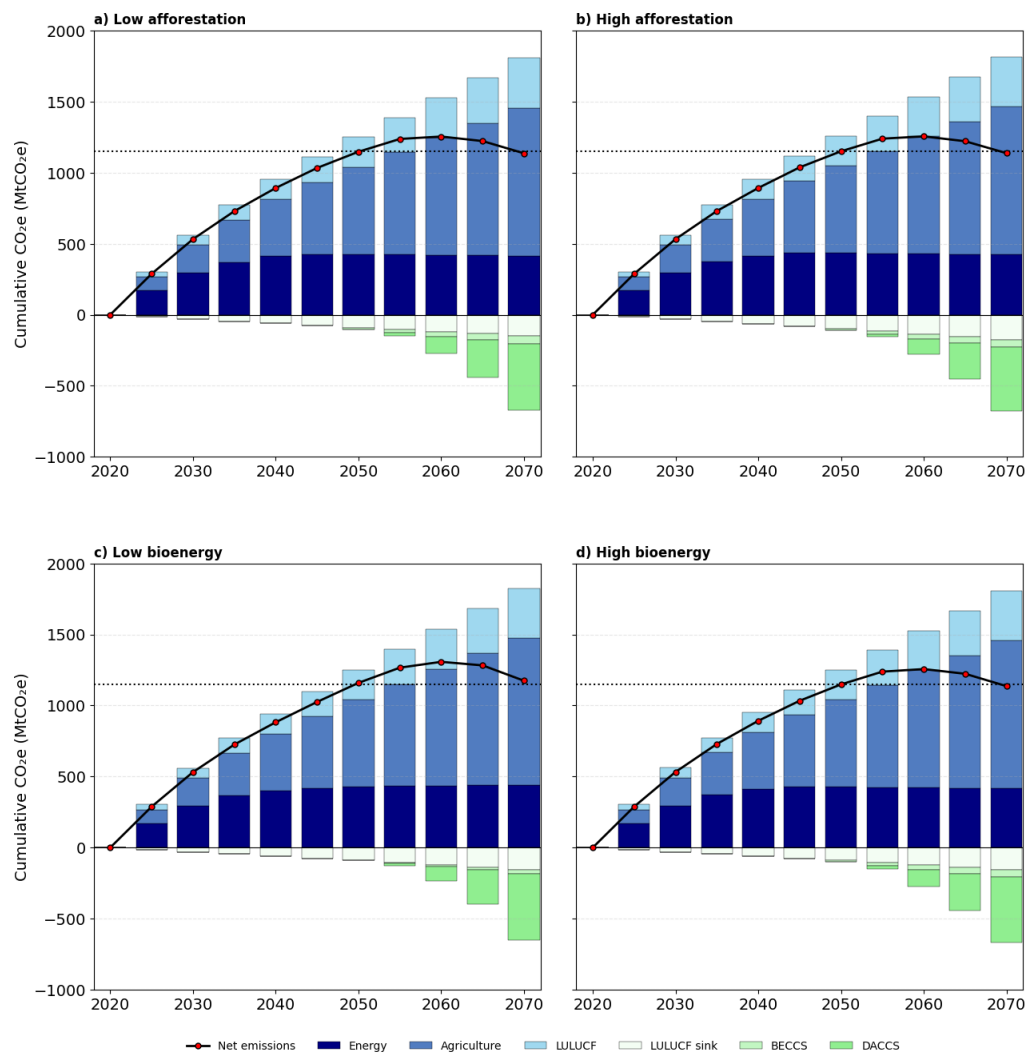
1043

1044 **Table A3: List of model variables**

Variable	Description	Unit
$ACT_{k,t}$	Activity level of technology or process (k) in period (t)	activity units
$L_{a,m,t}$	Land allocated to other uses on land type (m)	Mha
$L_{agri,m,t}$	Land allocated to agricultural production	Mha
$CONV_{m \rightarrow n,t}$	Land converted from land type (m) to land type (n)	Mha
ACT_t^{bio}	Bioenergy production activity	energy units



1045 **Appendix B**
1046 **B.1 Cumulative CO₂e graphs for marginal abatement costs scenarios**



1047 *Figure B1: Cumulative CO₂e for the marginal abatement diagnostic scenarios at five year intervals for the*
1048 *period 2020 to 2070. The cumulative emissions pathways are presented for a) Low afforestation, b) High*
1049 *afforestation, c) Low bioenergy, and d) High bioenergy scenarios. Stacked bars represent cumulative sectoral*
1050 *emissions and removals, and the black line with red markers shows cumulative net emissions. The dotted line*
1051 *denotes the 1150 Mt CO₂e carbon budget. The plots show the carbon budget overshoot and the subsequent*
1052 *reduction in cumulative emissions as engineered carbon removal is progressively deployed. The relatively*
1053 *small difference in cumulative emissions pathways in the low- and high-afforestation scenarios reflect land*
1054 *availability constraints—because livestock numbers are held constant in these scenarios, limited land is*
1055 *released from agricultural production for afforestation. Consequently, the higher afforestation rate cannot be*
1056 *maintained throughout the modelling horizon.*



1057 **Code and data availability**

1058 TIM-LEAF is developed as an extension of the TIM model and builds upon its underlying model
1059 structure and code. The source code and associated materials for TIM are available through its
1060 GitHub repository (<https://github.com/MaREI-EPMG/times-ireland-model>) and archived on Zenodo
1061 <https://doi.org/10.5281/zenodo.5708680> ; (Balyk et al., 2024). The code and data specific to TIM-
1062 LEAF, including the model implementation and materials required to reproduce the analysis
1063 presented in this study, are available through the corresponding repository:
1064 <https://github.com/MaREI-EPMG/TIM-LEAF/releases/tag/v1.0.0> and archived on
1065 <https://doi.org/10.5281/zenodo.22210894>.

1066 **Visualisation**

1067 The results generated using TIM-LEAF are available through an online interactive dashboard. The
1068 dashboard is hosted by the Energy Policy and Modelling Group (EPMG) and is accessible at:
1069 <https://epmg-dashboard>
1070 [2026.onrender.com/dashboard?study_id=18&tab=charts&scenario_id=90§or=SYS&subsector=](https://2026.onrender.com/dashboard?study_id=18&tab=charts&scenario_id=90§or=SYS&subsector=Total+Primary+Energy+Demand)
1071 [Total+Primary+Energy+Demand](https://2026.onrender.com/dashboard?study_id=18&tab=charts&scenario_id=90§or=SYS&subsector=Total+Primary+Energy+Demand)

1072 **Author contribution**

1073 **DJ:** Conceptualisation, model development, Python interface linking the TIM-LEAF and FaIR
1074 models, data analysis and manuscript preparation. **RM:** Acquisition and implementation of the FaIR
1075 Python script for Ireland, model validation, manuscript writing, reviewing and editing and
1076 supervision. **VA:** Model validation, results visualisation and manuscript reviewing and editing. **BS:**
1077 Technical development of the model, including troubleshooting, model calibration and validation.
1078 **ZH:** Development of the online dashboard and Python interface linking the TIM-LEAF and FaIR
1079 models. **HD:** Conceptualisation, model validation, manuscript writing, reviewing and editing, funding
1080 acquisition and supervision.

1081 **Competing interests**

1082 The authors declare that they have no conflict of interest.

1083 **Acknowledgements**

1084 The authors thank the TIMES-VEDA Forum for their prompt assistance with queries and the EtSAP-
1085 AFOLU team, particularly Daniele Mosso, Ida Græsted Jensen and Alessandro Chiodi, for valuable
1086 discussions that supported the development of the modelling framework. We thank the New
1087 Zealand Climate Change Commission for providing the modified version of the FaIR v2.1.3 source



1088 code. Thanks to Chris Smith who made the original modifications to the FaIR v2.1.3 source code.
1089 Special thanks to Aisling Murphy, Programme Manager at the EPMG, for her support during the
1090 preparation of this work.

1091 **Financial support**

1092 D.J, R.M and H.D are supported by the SELFS (Sustainable integrated pathways for carbon-
1093 negative energy, land and food systems) project (Grant No. 2022-CE-1137). This project is funded
1094 under the EPA Research Programme 2021-2030. The EPA Research Programme is a Government
1095 of Ireland initiative funded by the Department of the Environment, Climate and Communications.
1096 V.A, B.S and H.D are supported by the CAPACITY Project (Grant No. RFT2022/S 164-466018)
1097 funded by the Department of Climate, Energy and the Environment (DCEE), through the Climate
1098 and Energy Modelling Services to the Climate Energy Modelling Group (CEMG). Z.H is supported
1099 by MaREI, the Research Ireland Centre for Energy, Climate and Marine (Grant No.
1100 12/RC/2302_P2).

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