



LandSyMM-IMOGEN v1.0: a coupled land-system and climate-emulator framework for tracing land-management greenhouse-gas emissions through climate to ecosystem responses

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Abstract. Land use, management, and land-cover change account for approximately a quarter of anthropogenic greenhouse gas (GHG) emissions. Despite substantial progress in Earth system modelling, the CO₂, CH₄, and N₂O emissions arising specifically from land management remain incompletely accounted for, preventing closure of the feedback between management decisions, the resulting emissions, the climate response, and ecosystem impacts. Here we extend the LandSyMM modelling framework by coupling it with the intermediate-complexity climate emulator IMOGEN and by integrating IPCC Tier-1 agricultural-emission methods. The framework assembles a sector-complete, bottom-up emissions dataset by combining the SSP-RCP background emissions with socioeconomically driven land-use projections, Tier-1 agricultural emissions, and process-based land-biosphere fluxes. These emissions (not prescribed concentrations) drive the emulator, which converts them to atmospheric GHG concentrations and radiative forcing, and pattern-scales the result into climate, which in turn forces a final simulation of the resulting ecosystem trajectories.

Simulating the historical period and five Shared Socioeconomic Pathway-Representative Concentration Pathway (SSP-RCP) scenarios (SSP1-2.6 through SSP5-8.5), we evaluate the framework's reproduction of historical agricultural emissions, integrated emission and concentration trajectories, as well as climate-forcing patterns against established inventories (FAO-STAT, EDGAR), observational concentration records and global budgets, and the Inter-Sectoral Impact Model Intercomparison Project phase 3b (ISIMIP-3b) climate reference. LandSyMM reproduces historical agricultural GHG emissions across major source categories within the source-level uncertainty of the Tier-1 method (1970-2020): the agricultural CH₄ aggregate runs +19% high owing to IPCC default emission factors for the dominant livestock sources, while the N₂O aggregate is



near-balanced against FAOSTAT. With the complete natural-source terms included, the integrated emissions match the observationally constrained global budgets to within a few per cent at the present day. The prognostic atmospheric CO₂, CH₄, and N₂O concentration records are reproduced to within about 7 ppm, 50 ppb, and 6 ppb (root-mean-square over the historical period), subject to small end-of-period offsets. Relative to the unmodified reference-scenario anthropogenic emissions with the emulator's default natural baseline, our bottom-up integrated emissions – substituting the IPCC Tier-1 agricultural and LPJ-GUESS land-biosphere terms – diverge increasingly over the century: by 2100 the integrated CH₄ is 14 to 71% higher, while the explicit terrestrial carbon sink lowers the net CO₂ source by about 1 to 5 Pg C yr⁻¹. The emulated climate reproduces the ISIMIP-3b reference closely in both spatial pattern ($r \approx 0.98$ for temperature) and global-mean magnitude (within about 0.3 K across scenarios and analysis windows), leaving only a small residual regional mean-state difference that is near-neutral in the global mean. Returned to LPJ-GUESS, the two configurations settle to slightly different absolute carbon pools because they respond to different observation-based baseline climatologies (an initial-condition effect rather than a coupling signal), but compared on the meaningful basis of their changes over time they track each other closely, on a geography closely shared with the reference and with small, mixed crop-yield differences. Passed through IMOGEN, this lower net CO₂ source outweighs the higher CH₄ and lowers projected global-land-mean warming by about 0.2 to 0.5 K – a cooling that is largest (about 0.5 K) under the low-forcing SSP1-2.6 – and an identical-emulator diagnostic confirms this emission-pathway feedback is independent of the baseline climatology. The framework establishes a traceable platform for investigating the climate-ecosystem consequences of land-management GHG emissions, enabling explicit attribution of ecosystem responses to specific agricultural management practices.

1 Introduction

Land use, management, and land cover change (LUM/LCC) are primary contributors to global climate change and ecosystem state. Besides altering the biogeophysical land surface, these anthropogenic pressures change the atmospheric concentrations of the three major greenhouse gases (GHGs) – carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) (Hong et al., 2021; Masson-Delmotte et al., 2021; Pongratz et al., 2018). Human activities have elevated atmospheric CO₂, CH₄, and N₂O concentrations by approximately 47%, 156%, and 23% above pre-industrial baselines (Masson-Delmotte et al., 2021), respectively, with direct consequences for global temperature and hydrological regimes (Friedlingstein et al., 2023; Saunio et al., 2020; Tian et al., 2024).

Agricultural and food production systems are the primary socioeconomic drivers of these LUM/LCC emission pathways (Alexander et al., 2017; Molotoks et al., 2020; Robinson et al., 2018). Agricultural expansion-driven deforestation, wood harvest, and the decomposition of cleared residues constitute the largest share of land-based CO₂ emissions (Friedlingstein et al., 2023; Hurtt et al., 2020). The two dominant non-CO₂ agricultural emission pathways are (i) N₂O from synthetic nitrogen fertiliser application and manure management, through microbial nitrification and denitrification in agricultural soils; and (ii) CH₄ from enteric fermentation in ruminant livestock, rice cultivation under anaerobic flooding conditions, and anaerobic decomposition of stored manure (Hong et al., 2021; McDaniel et al., 2019). Collectively, LUM and LCC represent the largest



single-sector non-energy component of the global GHG budget (Hong et al., 2021), with agricultural intensification independent of land conversion accounting for approximately 35% of recent non-CO₂ emission increases (Saunio et al., 2020). With the global human population, about 8.0 billion in 2022, projected to reach approximately 9.7 billion by 2050 and to approach 10 billion by 2060 under median projections (United Nations Department of Economic and Social Affairs, Population Division, 2022), the growing demand for food, feed, and fuel will further amplify LUM pressures. Historical estimates indicate that LUM and LCC accounted for 27% of total anthropogenic GHG emissions from 1961 to 2017 (Hong et al., 2021).

In this context, we distinguish between ‘top-down’ and ‘bottom-up’ emission estimates: top-down approaches prescribe aggregate sectoral GHG totals directly from integrated assessment model (IAM) scenario outputs (O’Neill et al., 2016), whereas bottom-up approaches compute emissions from granular activity data (e.g., land-use areas, livestock counts, fertiliser application rates) via mechanistic or inventory-based methods that preserve the causal links from the management decision to the resulting emission. Despite substantial progress in Earth system modelling, the non-CO₂ greenhouse-gas emissions from agriculture and land management remain incompletely represented in existing coupled frameworks. While many full ESMs (e.g., UKESM1, CESM2) now simulate interactive land carbon (Danabasoglu et al., 2020; Sellar et al., 2019) including the CO₂ fluxes of deforestation and regrowth, the agricultural and management-related CH₄ and N₂O emissions are typically prescribed from top-down IAM scenario trajectories rather than computed dynamically from bottom-up, socioeconomically driven land use and management. IAM-hybrid frameworks likewise prescribe these sectoral totals (Alexander et al., 2018; Henry et al., 2022). This top-down prescription means that the feedbacks between specific agricultural management decisions (e.g., nitrogen fertiliser rates, livestock herd composition, irrigated rice area), their resulting GHG emissions, the resulting climate response, and the subsequent impact of that climate on agricultural productivity and ecosystem state cannot be closed within a single consistent framework. Consequently, it remains difficult to perform controlled experiments that isolate the contribution of specific agricultural emission sources to global climate-ecosystem trajectories, or to trace how socioeconomically plausible shifts in the food system propagate through the coupled Earth system. Dynamically coupled frameworks that internalise this feedback process – from socioeconomic land-use decisions and corresponding bottom-up GHG emission inventories to climate emulation and ecosystem response – are therefore needed to provide process-consistent, mechanistically attributable insights into global climate-ecosystem feedback dynamics (Huntingford et al., 2010).

Here we integrate the Land System Modular Model (LandSyMM) – comprising the LPJ-GUESS dynamic global vegetation model (Smith et al., 2014) and the Parsimonious Land Use Model (PLUM) (Alexander et al., 2018) – with the Intermediate Model for the Global Environment (IMOGEN) climate emulator (Huntingford et al., 2010) to quantify the impact of agricultural changes on ecosystem responses via CO₂, CH₄, and N₂O emissions and feedbacks. LPJ-GUESS provides PLUM with mechanistic potential yield responses to climate and management, while PLUM projects future land area fractions and management intensities (i.e., irrigation, fertiliser) according to Shared Socioeconomic Pathways (SSPs). We combine these bottom-up projections with IPCC Tier-1 methodologies and land-biosphere fluxes to drive IMOGEN, which emulates the climate response. This climate is then fed back into LPJ-GUESS to assess the related global ecosystem responses. The LandSyMM framework thus provides a quantitative platform for assessing how socioeconomically driven agricultural emission pathways propagate through the coupled climate-ecosystem system under divergent future scenarios.



Specifically, this paper has three objectives: (1) to describe the architecture, coupling protocol, and emissions-integration methodology of the LandSyMM framework, including the Intermediary Controller that enables sequential, bottom-up emissions-driven climate-ecosystem coupling; (2) to evaluate the historical performance of the framework’s agricultural emission modules against observed inventories (FAOSTAT and the Emissions Database for Global Atmospheric Research, EDGAR) over 1970-2020; and (3) to evaluate the capacity of LandSyMM to reproduce global GHG emission and concentration trajectories, climate-forcing patterns, and ecosystem-state responses, benchmarked against independent observational records and budgets, the harmonised emissions of the Reduced Complexity Model Intercomparison Project (RCMIP; CMIP6), and the bias-corrected reference climate of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP-3b), across the five Shared Socioeconomic Pathway-Representative Concentration Pathway (SSP-RCP) scenarios (SSP1-2.6 through SSP5-8.5) over 1900-2100.

95 2 Methods

2.1 The LandSyMM framework

LandSyMM is a spatially explicit, emissions-driven coupled modelling framework designed to investigate the interactions between socioeconomically driven agricultural land use and management (LUM), bottom-up GHG emissions (CO_2 , CH_4 , N_2O), the global climate response, and terrestrial ecosystem dynamics (Fig. 1). LandSyMM is an established, modular land-system framework (Alexander et al., 2018; Rabin et al., 2020) whose design has long anticipated coupling its land-system components to a climate emulator; the present work realises that capability by embedding IMOGEN, thereby closing the link between land-management emissions and the simulated climate that drives ecosystem responses. The framework integrates three established component models – the Parsimonious Land Use Model (PLUM) (Alexander et al., 2018; Engström et al., 2016), the LPJ-GUESS dynamic global vegetation model (Smith et al., 2014), and the IMOGEN intermediate-complexity climate emulator (Huntingford et al., 2010; Zelazowski et al., 2018). It incorporates bottom-up IPCC Tier-1 inventory calculations for agricultural CH_4 and N_2O emissions, and a dedicated Intermediary Controller (IC) that manages coupling, emissions integration, and boundary harmonisation. To embed the climate emulator within a single modelling system, the IMOGEN code (originally implemented in Fortran) was re-implemented in C++ and integrated directly into the LPJ-GUESS code base, so that the climate emulation runs within the same executable as the dynamic vegetation model. The framework supports closed-loop (interactive) coupling; in the configuration presented here the components are executed in a sequential coupled mode (Sect. 2.4), with fully interactive runtime feedback identified as the next development step (Sect. 4).

In brief: PLUM generates global trajectories of cropland and pasture area, fertiliser and irrigation intensities, and livestock populations from socioeconomic drivers and biophysical yield constraints provided by LPJ-GUESS. These land-use and management outputs drive an inventory-based computation of agricultural CH_4 and N_2O emissions (Sect. 2.2), which are combined with the LPJ-GUESS process-based land-biosphere fluxes (CO_2 , CH_4 and N_2O) and residual non-agricultural background emissions into a sector-complete annual forcing dataset. This integrated emissions dataset drives IMOGEN, which emulates the resulting global climate response and returns spatially explicit monthly climate fields to force a final LPJ-GUESS simulation of realised ecosystem trajectories. Full descriptions of the three established component models are provided in Ap-

pendix B (LPJ-GUESS, B1; PLUM v2, B2; IMOGEN, B3); the full coupling architecture, cadence, and data flow protocol are
 120 described in Sect. 2.4.

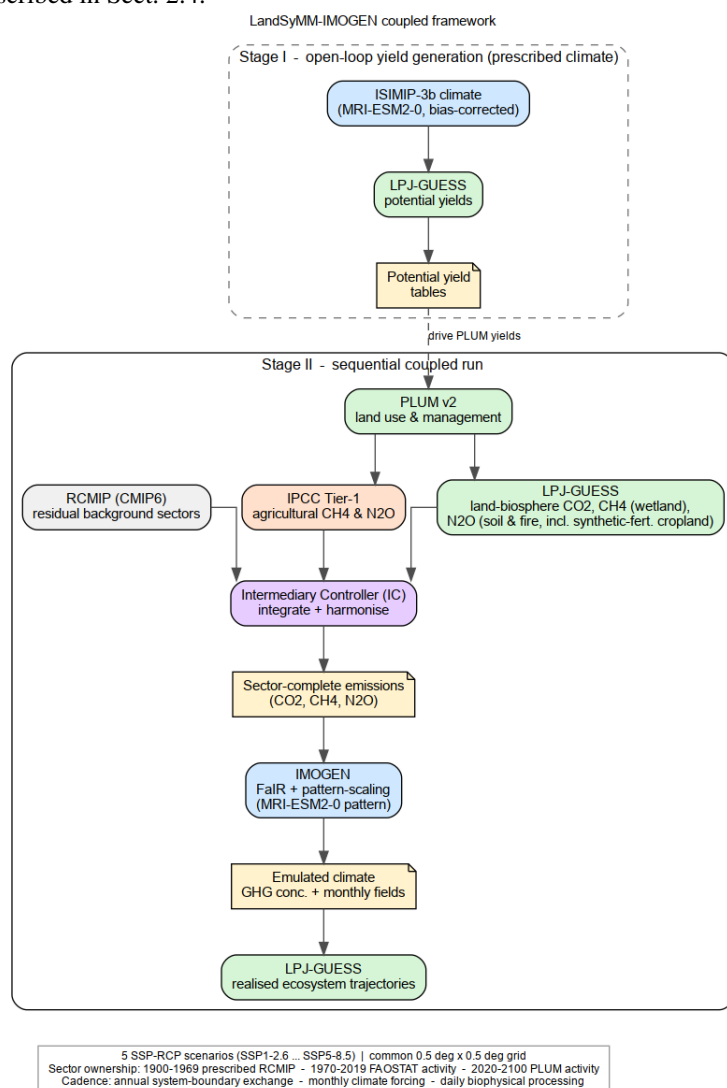


Figure 1. Schematic overview of the LandSyMM-IMOGEN coupled framework. Stage I (top; open loop): LPJ-GUESS is driven by prescribed ISIMIP-3b (MRI-ESM2-0) climate forcing to generate potential yield tables for PLUM. Stage II (bottom; sequential coupled run): PLUM land-use/management outputs and IPCC Tier-1 agricultural emissions are combined by the Intermediary Controller (IC) with LPJ-GUESS process-based fluxes and residual RCMIP (CMIP6) background sectors to form a sector-complete emissions time series. This integrated dataset forces IMOGEN, which derives atmospheric GHG concentrations and pattern-scaled monthly climate anomalies to drive a final LPJ-GUESS simulation of realised ecosystem trajectories. The coupling clock operates on three nested timescales: annual system-boundary exchanges, monthly climate forcing within each year, and daily biophysical processing within each month. Temporal sector ownership is segmented across three periods:



130 1900-1969 (prescribed RCMIP); 1970-2019 (FAO activity data); 2020-2100 (PLUM activity data). All inter-module exchanges occur on a common $0.5^\circ \times 0.5^\circ$ global grid.

The specific code version used throughout this study is LPJ-GUESS v4.1 (trunk revision r13078), compiled with the embedded C++ implementation of IMOGEN (Appendix B3) and coupled to PLUM v2 (Appendix B2) through the Intermediary Controller (Sect. 2.4.1). The corresponding source and configuration are archived at the DOI given in the Code and Data
 135 Availability section.

Because the C++ re-implementation of IMOGEN is the principal technical contribution of this framework, it was verified against the original Fortran IMOGEN under identical forcing, configuration, and pattern and energy-balance calibration. Driven by the same inputs, the two engines produce the same global-mean climate response. Over 1900-2100 under SSP5-8.5, the C++ and Fortran implementations agree in the global-land-mean near-surface temperature to within 0.11 K (well within the
 140 simulated interannual variability), with the pattern-scaled anomaly applied uniformly across all twelve months in both. The prognostic CH_4 and N_2O concentrations are identical between the two engines, as they are prescribed pass-throughs to the radiative-forcing module. The prognostic CO_2 concentration agrees to within a small secular offset (up to about 30 ppm by 2100, growing with cumulative emissions), consistent with differences in the numerical integration of the carbon-cycle box model between the two implementations (including the double-precision arithmetic of the C++ relative to the single-precision
 145 Fortran). The temperature response is unaffected to within 0.11 K. The re-implementation therefore reproduces the behaviour of the established Fortran emulator, so the coupled-minus-reference differences reported in Sect. 3.3 are properties of the coupled system rather than artefacts of the re-implementation. The verification configuration is archived with the code (Sect. Code and Data Availability).

2.2 Agricultural, land use and management GHG modelling pipeline: IPCC methodologies

150 We estimate global GHG emissions from agricultural production and land use using the IPCC Tier-1 methodologies (2006 Guidelines; 2019 Refinement). Tier-1 methods combine specific activity data (i.e., land area, livestock populations, nutrient application rates) with globally or regionally averaged default emission factors (Garg et al., 2006). In the LandSyMM framework we apply these Tier-1 formulations specifically to the following agricultural non- CO_2 sources: methane (CH_4) from enteric fermentation, manure management, and rice cultivation, and nitrous oxide (N_2O) from managed soils and manure
 155 management. We combine PLUM activity data (e.g., livestock populations, crop areas, and fertiliser application) with source-specific default emission factors and physiological constants. Carbon dioxide (CO_2), together with the land-biosphere CH_4 and N_2O fluxes, is not computed by the Tier-1 inventory. These are generated from process-based simulations within LPJ-GUESS (Sects. 2.2.6-2.2.8), consistent with the model's mechanistic treatment of vegetation, soil, and disturbance dynamics. By using this empirical framework, the model translates the socioeconomic trajectories generated by PLUM into mass-based emissions,
 160 ensuring that the inventory remains computationally efficient while capturing the first-order impacts of agricultural intensification and land-use change. Emissions are reported in the native units of each IPCC source category (typically kg, Gg, or Tg per year), consistent with IPCC reporting conventions. The Intermediary Controller (IC) performs unit harmonisation before

integration: all emission components are converted to a common unit of Tg yr^{-1} for each gas species prior to summation and delivery to IMOGEN (see Sect. 2.4.4). Unit abbreviations follow SI conventions: $1 \text{ Tg} = 10^3 \text{ Gg} = 10^6 \text{ t} = 10^9 \text{ kg} = 10^{12} \text{ g}$.

165 The same Tier-1 accounting is applied consistently across the full period, differing only in the activity data that drive it: FAO activity data over the historical period (1970-2019) and the PLUM projections of land-area fractions, management intensities, and livestock populations over the scenario period (2020-2100) (Sect. 2.3.1). The principal Tier-1 parameters (i.e., livestock nitrogen and volatile-solid excretion rates, typical animal masses, animal-waste-management-system distributions, and the source-specific emission factors) are IPCC regional defaults assigned by climate-zone classification and are held constant
 170 through time, consistent with the Tier-1 method (the projection-period implications are noted in Sect. 2.4.5). The formulations for each source category are given in Sects. 2.2.1-2.2.5.

2.2.1 Methane emissions from enteric fermentation

PLUM represents livestock through commodity-based categories defined by economic output. To translate these into a greenhouse-gas inventory, we apply an intermediary mapping that aligns PLUM's livestock commodities with the physiological categories
 175 of the IPCC guidelines (Table 1). This mapping is defined and applied within the Intermediary Controller and is independent of PLUM's internal economic accounting.

Table 1. Mapping of PLUM livestock commodities to IPCC physiological categories.

PLUM commodity category	IPCC physiological category
Meat cattle	Other cattle
Milk, whole fresh cow	Dairy cattle
Meat buffalo	Buffalo
Meat sheep; milk, whole fresh sheep	Sheep
Meat goat; milk, whole fresh goat	Goats
Meat pig	Swine
Meat poultry; eggs, primary; ducks	Poultry/hens
Asses; mules; camels; horses	Asses, mules, camels, horses

Enteric fermentation is the largest agricultural source of CH_4 and is dominated by ruminant livestock (Gavrilova et al., 2019). For cattle and buffalo, whose emissions are strongly sensitive to regional diet and management, we apply region-specific
 180 Tier-1 emission factors from IPCC Table 10.11 across nine IPCC world regions (North America, Western Europe, Eastern Europe, Oceania, Latin America, Africa, the Middle East, Asia, and the Indian Subcontinent). Dairy and non-dairy cattle are treated separately: the dairy herd is identified from reported milking-animal numbers (capped at the total cattle stock), and the remaining animals are assigned to non-dairy ("other") cattle. For sheep and goats, Tier-1 emission factors are assigned by productivity system following IPCC Table 10.10, applying high-productivity factors in developed regions and low-productivity



185 factors elsewhere (Table 10.10, footnote 1). Horses, mules, asses, and camels – minor hindgut and foregut fermenters – are included using the single global Tier-1 factors of Table 10.10 (18, 10, 10, and 46 kg CH₄ head⁻¹ yr⁻¹, respectively).

Monogastric livestock (swine and poultry) are excluded from the enteric inventory: poultry have no rumen (the 2019 Refinement gives no poultry enteric emission factor), and swine enteric CH₄ is below 1% of the total (retained only in the historical evaluation for comparability with FAO). Their manure CH₄ and N₂O are accounted for in the manure-management inventories
190 (Sects. 2.2.2 and 2.2.4).

Per-species annual emissions are computed with the IPCC Tier-1 formulation (Eq. 10.19),

$$E_{(T)} = \frac{EF_{(T)} N_{(T)}}{10^6}, \quad (1)$$

and summed across livestock categories to give the total enteric flux (Eq. 10.20),

$$E_{\text{CH}_4, \text{enteric}} = \sum_T E_{(T)}, \quad (2)$$

195 where $E_{(T)}$ is the annual CH₄ emission from livestock category T (kt CH₄ yr⁻¹), $EF_{(T)}$ is the corresponding region- and productivity-specific emission factor (kg CH₄ head⁻¹ yr⁻¹), $N_{(T)}$ is the head count (from FAO over the historical evaluation period and from PLUM over the scenario period), and the factor 10⁶ converts kg to kt. Over the scenario period, the populations of the minor non-PLUM species (horses, mules, asses, and camels) are held at their FAO 2020 regional totals, as PLUM does not project these stocks. Driven by the SSP socioeconomic trajectories, the resulting bottom-up inventory propagates shifts in
200 the geographical distribution and size of livestock populations through to atmospheric CH₄ via the coupled IMOGEN emulator.

2.2.2 Methane emissions from manure management

Methane is produced during the anaerobic decomposition of organic matter in livestock manure. The yield depends on the mass of volatile solids (VS) excreted and the manure-management system (MMS) in which the manure is stored (Gavrilova et al., 2019). We follow the IPCC 2019 Refinement Tier-1 methodology (Eqs. 10.22-10.23). PLUM supplies the livestock
205 head counts. All physiological and management parameters (i.e., the VS excretion rate, typical animal mass (TAM), maximum methane-producing capacity (B_0), methane conversion factors (MCF), and the allocation of manure across management systems (AWMS)) are IPCC regional defaults and are independent of PLUM.

The annual VS excreted per animal of category T in region r follows from the regional default excretion rate and the typical animal mass (Eq. 10.22):

$$210 \quad VS_{(T,r)} = \frac{\text{VSrate}_{(T,r)} \times \text{TAM}_{(T,r)}}{1000} \times 365, \quad (3)$$

where $\text{VSrate}_{(T,r)}$ is the daily VS excretion (kg VS per 1000 kg animal mass; IPCC Table 10.13A), $\text{TAM}_{(T,r)}$ is the typical animal mass (kg head⁻¹; Table 10A.5), the factor 1000 normalises the animal-mass unit, and 365 annualises.



The per-head manure CH_4 emission factor combines this VS yield with the maximum methane-producing capacity and the management mix (IPCC Eq. 10.23):

$$EF_{(T,r)} = VS_{(T,r)} \times B_{0,(T,r)} \times 0.67 \times \sum_S (\text{MCF}_{(S,k)} \text{AWMS}_{(T,S,r)}), \quad (4)$$

where $B_{0,(T,r)}$ is the maximum methane-producing capacity ($\text{m}^3 \text{CH}_4 \text{ kg}^{-1} \text{VS}$; Table 10.16A), the factor 0.67 kg m^{-3} converts volumetric to mass CH_4 , $\text{MCF}_{(S,k)}$ is the methane conversion factor (applied as a fraction; the percentage values tabulated in Appendix A Table A6 are divided by 100) for management system S in the climate zone k assigned to region r (Table 10.17), and $\text{AWMS}_{(T,S,r)}$ is the fraction of manure handled in system S for species T in region r (Tables 10A.6-10A.9).

The summation runs over the nine manure-management systems represented: uncovered anaerobic lagoon, liquid/slurry, solid storage, dry lot, pasture/range/paddock (PRP), daily spread, anaerobic digester, burned for fuel, and a residual (“other”) category. For swine, short- and long-retention pit storage replace the PRP and burned-for-fuel systems. Total annual manure CH_4 for each category is the product of the PLUM head count and $EF_{(T,r)}$, summed across categories.

Each IPCC region is assigned a single dominant Table 10.17 climate zone for MCF selection (Table 3). Manure CH_4 is computed for all major livestock categories, including poultry (laying hens, broilers, and ducks), whose manure is a non-negligible source of CH_4 (and N_2O ; Sect. 2.2.4) even though poultry enteric emissions are excluded (Sect. 2.2.1). PLUM commodity categories are mapped to the IPCC manure categories following Table 2.

Table 2. Mapping of PLUM livestock commodities to IPCC categories for manure-management parameter assignment (VS rate, TAM, B_0 , and AWMS).

PLUM commodity	IPCC manure category
Milk, whole fresh cow	Dairy cattle
Meat cattle	Other (non-dairy) cattle
Meat buffalo	Buffalo
Meat pig	Swine
Eggs, primary	Laying hens
Meat poultry	Broilers
Ducks	Ducks
Meat sheep; milk, whole fresh sheep	Sheep
Meat goat; milk, whole fresh goat	Goats
Asses; mules; horses	Equines
Camels	Camels

Table 3. Assignment of IPCC world regions to IPCC Table 10.17 climate zones for selection of manure-management methane conversion factors (MCF).



IPCC world region	Climate zone (Table 10.17)
North America, Western Europe, Eastern Europe	Cool Temperate Moist
Oceania, Asia	Warm Temperate Moist
Middle East	Warm Temperate Dry
Latin America, Africa, Indian Subcontinent	Tropical Moist

2.2.3 Methane emissions from rice cultivation

Methane is produced in flooded rice paddies by the anaerobic decomposition of soil organic matter by methanogens. We estimate rice CH₄ following the IPCC 2019 Refinement Tier-1 method (Vol. 4, Ch. 5 (Ogle et al., 2019); Eqs. 5.1-5.3), driven by the PLUM rice-harvested area. Total annual emissions are obtained by summing over rice sub-region i and water-regime class j :

$$CH_{4,\text{rice}} = \sum_{i,j} (EF_{i,j} \times t_i \times A_{i,j} \times 10^{-6}), \quad (5)$$

where $EF_{i,j}$ is the adjusted daily emission factor (kg CH₄ ha⁻¹ day⁻¹), t_i the regional cultivation period (days), $A_{i,j}$ the harvested area (ha) of water class j in region i , and 10^{-6} converts kg to Gg CH₄ (the Intermediary Controller subsequently harmonises all module outputs to a common Tg yr⁻¹ unit; Sect. 2.4.4).

The adjusted daily emission factor scales a regional baseline factor by the water-regime, pre-season, and organic-amendment conditions (IPCC Eq. 5.2):

$$EF_{i,j} = EFC_i \times SF_{w,j} \times SF_p \times SF_{o,j}, \quad (6)$$

with EFC_i the baseline daily factor for continuously flooded fields without organic amendments (region-specific; IPCC Table 5.11, reproduced in Table 4), $SF_{w,j}$ the water-regime scaling factor, SF_p the pre-season factor, and $SF_{o,j}$ the organic-amendment factor. The organic-amendment factor follows IPCC Eq. 5.3:

$$SF_{o,j} = \left(1 + \sum_n ROA_n CFA_n \right)^{0.59}, \quad (7)$$

where ROA_n is the application rate of organic amendment n (t dry matter ha⁻¹) and CFA_n its conversion factor (IPCC Table 5.14).

Because PLUM does not resolve sub-national flooding regimes, the two emitting water-regime classes are inferred from the PLUM applied-irrigation field: rice area receiving applied irrigation is assigned the irrigated aggregated-case factor ($SF_w = 0.60$; IPCC Table 5.12) and the remainder the rainfed-lowland factor ($SF_w = 0.45$). The pre-season is taken as non-flooded



for fewer than 180 days ($SF_p = 1.0$; Table 5.13). Irrigated rice receives a straw-incorporation amendment (application rate 2 t ha⁻¹ dry matter, the global median of Yan et al. (2005), with the *CFOA* for straw incorporated shortly before cultivation; Table 5.14), whereas rainfed rice receives none ($SF_o = 1.0$, straw typically burned or removed). Baseline factors EF_{C_i} and cultivation periods t_i are assigned by IPCC rice sub-region (Table 4). The model's nine world regions are mapped onto the seven IPCC rice sub-regions for this assignment, with regions of negligible rice area taking the global-estimate (Africa) values.

This treatment lets the irrigated fraction – and hence the area-weighted emission factor – evolve endogenously with the PLUM scenarios. Three Tier-1 simplifications should be noted: (i) PLUM preferentially routes irrigation to high-yield commercial systems, so several major Asian producers appear as predominantly irrigated (e.g., India is close to fully irrigated in PLUM versus roughly half in IRRI statistics (Pandey et al., 2010)), which raises modelled emissions relative to a finer split; (ii) upland rice ($SF_w = 0$) is not represented separately and its small area is absorbed into the rainfed class; and (iii) a single global straw-amendment rate is applied in the absence of sub-national data. The soil-type and cultivar scaling factors (SF_s , SF_r) are Tier-2 refinements and are not applied. The organic-amendment factor is evaluated in the summed form of Eq. (7) (a single irrigated straw amendment, $SF_o = (1 + 2.0 \times 1.0)^{0.59} = 1.91$).

Table 4. IPCC rice sub-region baseline daily emission factors (EF_c ; IPCC Table 5.11, 2019 Refinement) and default cultivation periods (t ; Table 5.11A).

Rice sub-region	EF_c (kg CH ₄ ha ⁻¹ day ⁻¹)	t (days)
East Asia	1.32	112
Southeast Asia	1.22	102
South Asia	0.85	112
Europe	1.56	123
North America	0.65	139
South America	1.27	124
Africa (global estimate)	1.19	113

2.2.4 Nitrous oxide (N₂O) emissions from manure management

Nitrous oxide is produced from manure nitrogen (N) both *directly*, through nitrification and denitrification within the manure-management system, and *indirectly*, following the volatilisation of manure N (as NH₃ and NO_x) and its subsequent redeposition. We estimate both pathways with the IPCC 2019 Refinement Tier-1 method (our Eqs. 8-10), driven by the PLUM head counts and the same regional excretion and management parameters used for manure CH₄ (Sect. 2.2.2).

The annual N excreted per animal of category T in region r is obtained from the regional default excretion rate and typical animal mass (IPCC Eq. 10.30):

$$Nex_{(T,r)} = \left(N_{rate(T,r)} \times \frac{TAM_{(T,r)}}{1000} \right) \times 365, \quad (8)$$



where $N_{\text{rate}(T,r)}$ is the daily N excretion rate (kg N per 1000 kg animal mass; IPCC Table 10.19) and $TAM_{(T,r)}$ the typical animal mass (kg head⁻¹; Table 10A.5). Direct N₂O emissions are obtained by routing the excreted N through the regional AWMS distribution and applying system-specific direct emission factors (IPCC Eq. 10.25):

$$N_2O_{\text{mm,dir}} = \left[\sum_S \left(\sum_T N_{(T,r)} \text{Nex}_{(T,r)} \times AWMS_{(T,S,r)} \right) \times EF_{3(S)} \right] \times \frac{44}{28}, \quad (9)$$

280 and the indirect (volatilisation) pathway applies the volatilised fraction and the indirect emission factor EF_4 (IPCC Eqs. 10.26-10.27):

$$N_2O_{\text{mm,ind}} = \left[\sum_S \left(\sum_T N_{(T,r)} \text{Nex}_{(T,r)} \times AWMS_{(T,S,r)} \times \text{Frac}_{\text{gas},S} \right) \times EF_4 \right] \times \frac{44}{28}, \quad (10)$$

with total manure-management N₂O given by their sum. Here $N_{(T,r)}$ is the PLUM head count, $AWMS_{(T,S,r)}$ the fraction of excreted N managed in system S (the same nine-system regional distribution as for manure CH₄; Tables 10A.6-10A.9),
 285 $EF_{3(S)}$ the direct emission factor for system S (kg N₂O-N per kg N; Table 10.21), $\text{Frac}_{\text{gas},S}$ the fraction of managed N volatilised in system S (Table 10.22), $EF_4 = 0.010$ kg N₂O-N per kg N volatilised, and 44/28 converts N₂O-N mass to N₂O mass.

PLUM livestock commodities are mapped to the IPCC categories exactly as for manure CH₄ (Table 2), so that N_{rate} and TAM are assigned consistently across the two manure modules. Poultry are represented with a single direct emission factor and
 290 volatilisation fraction rather than an MMS-resolved distribution; equines (horses, mules, and asses) are omitted as a negligible manure-N₂O source. As at Tier-1 without sub-national data, the AWMS fractions are held at their regional default values, and the leaching pathway of indirect N₂O (IPCC Eqs. 10.28-10.29) is not included, consistent with its minor and data-limited contribution from managed manure.

2.2.5 Direct nitrous oxide (N₂O) emissions from managed soils

295 Nitrous oxide emissions from managed soils are estimated with the IPCC 2019 Refinement Tier-1 method (Vol. 4, Ch. 11 (Hergoualc'h et al., 2019)), which attributes both direct and indirect N₂O to the nitrogen added to, or mineralised within, agricultural soils. Five nitrogen sources are represented: synthetic fertiliser (F_{SN}), organic manure applied to soils (F_{ON}), nitrogen in crop residues returned to the field (F_{CR}), nitrogen mineralised from drained organic soils (F_{SOM}), and nitrogen deposited by grazing animals on pasture, range, and paddock (F_{PRP}). F_{SN} is taken from the PLUM fertiliser-application
 300 field; F_{ON} and F_{PRP} are derived from the same livestock excretion and AWMS parameters as the manure modules (Sects. 2.2.2, 2.2.4), with each species' annual N excretion partitioned into the fraction routed to managed systems and applied to soils (F_{ON}) and the fraction deposited directly during grazing (F_{PRP}). F_{CR} is computed from PLUM crop production and the IPCC residue parameters (Table 11.2), and F_{SOM} is held at its FAO 2020 baseline, as no Tier-1 scenario projection exists for organic-soil drainage. In the integrated dataset the Tier-1 modules own the agricultural managed-soil N₂O that LPJ-GUESS



305 does not resolve mechanistically. This includes the manure-applied (F_{ON}), crop-residue (F_{CR}), drained-organic-soil (F_{SOM}) and grazing-deposition (F_{PRP}) sources and their associated indirect pathways. Process-based LPJ-GUESS simulations supply the synthetic-fertiliser cropland N_2O emission. This includes the direct and associated indirect (volatilisation and leaching) soil emission, together with the natural and land-use-change-induced soil and fire N_2O emission (Sect. 2.2.8). The synthetic-fertiliser Tier-1 direct and indirect terms are correspondingly excluded from the integrated dataset. Equation (11) states the
 310 complete Tier-1 method, including the synthetic-fertiliser term F_{SN} , as used in the historical evaluation of the method against FAOSTAT (Sect. 3.1). In assembling the integrated dataset the synthetic-fertiliser cropland source is taken from the process-based model, so that each source is represented exactly once.

Direct emissions apply the aggregate emission factor EF_1 to the summed nitrogen inputs (IPCC Eq. 11.1):

$$N_2O_{dir} = (F_{SN} + F_{ON} + F_{CR} + F_{SOM} + F_{PRP}) \times EF_1 \times \frac{44}{28}. \quad (11)$$

315 Indirect emissions follow from the atmospheric redeposition of volatilised nitrogen and from leaching and runoff. The volatilisation pathway applies source-specific volatilised fractions and the indirect factor EF_4 (IPCC Eq. 11.9):

$$N_2O_{vol} = (F_{SN} Frac_{GASF} + F_{ON} Frac_{GASM} + F_{PRP} Frac_{GASM}) \times EF_4 \times \frac{44}{28}, \quad (12)$$

and the leaching pathway applies the leached fraction and EF_5 (IPCC Eq. 11.10):

$$N_2O_{lea} = (F_{SN} + F_{ON} + F_{CR} + F_{PRP}) \times Frac_{LEACH} \times EF_5 \times \frac{44}{28}, \quad (13)$$

320 with total managed-soil N_2O given by the sum of the three terms and $44/28$ converting N_2O -N to N_2O . Parameter values follow the 2019 Refinement (Table 5). A single aggregate EF_1 is applied to all direct N sources because PLUM does not disaggregate fertiliser by chemical form. Leaching is set to zero in dry regions, where it is assumed negligible.

The crop-residue term is calibrated to the historical inventory: PLUM reports production for aggregated crop groups (e.g., combined fruit-and-vegetable and energy-crop categories) whose raw residue-N estimate exceeds the crop-specific historical
 325 value, so a single global scale factor (i.e., the ratio of the historical to the raw-PLUM residue N in the 2020 base year) is applied so that the residue-N flux remains consistent with the historical estimate.

Table 5. IPCC 2019 Refinement Tier-1 parameters for managed-soil N_2O (Table 11.3).

Parameter	Description	Value
EF_1	Direct emission factor for soil N inputs	$0.010 \text{ kg } N_2O\text{-N (kg N)}^{-1}$
EF_4	Indirect emission factor (volatilisation/redeposition)	$0.010 \text{ kg } N_2O\text{-N (kg N)}^{-1}$



Parameter	Description	Value
EF_5	Indirect emission factor (leaching/runoff)	$0.011 \text{ kg N}_2\text{O-N (kg N)}^{-1}$
$Frac_{GASF}$	Fraction of synthetic N volatilised	0.11
$Frac_{GASM}$	Fraction of organic / grazing N volatilised	0.21
$Frac_{LEACH}$	Fraction of N lost to leaching / runoff	0.24 (0 in dry regions)
44/28	$\text{N}_2\text{O-N} \rightarrow \text{N}_2\text{O}$ mass conversion	1.571

2.2.6 Land-biosphere carbon dioxide (CO_2) fluxes

Unlike the activity-based CH_4 and N_2O inventories, the land-biosphere carbon dioxide component is derived mechanistically from LPJ-GUESS.

LPJ-GUESS resolves the ecosystem carbon balance at a daily time step. Net primary production is the difference between gross primary production and autotrophic respiration,

$$NPP = GPP - R_a, \quad (14)$$

and the assimilated carbon is allocated to plant tissues before entering the soil organic-matter pools, from which it is returned to the atmosphere by heterotrophic respiration (R_h). In the land-use-coupled configuration used here, the model reports the net land-atmosphere CO_2 flux of each grid cell (F_{net}) as the signed sum of the ecosystem and land-management carbon fluxes,

$$F_{\text{net}} = (R_h + R_{\text{fire}} - NPP) + F_{\text{LUM}}, \quad (15)$$

where R_{fire} is the fire carbon emission and F_{LUM} collects the net carbon exchange associated with land use and management (establishment, reproduction, harvest removals, manure inputs, seeding, land-use change, and product-pool turnover). Because F_{net} includes fire and land-use and management exchanges, it is a net-biome-production-type flux rather than net ecosystem exchange (NEE). We therefore report F_{net} rather than NEE. The LPJ-GUESS v4.1 sign convention is used throughout: a positive value denotes a net flux to the atmosphere (carbon source) and a negative value net uptake (carbon sink). F_{net} is read directly from the model output rather than recomputed.

To obtain total fluxes, the per-area values ($\text{kg C m}^{-2} \text{ yr}^{-1}$) are integrated over the grid. The area of each 0.5° cell is computed as a function of latitude ϕ to account for the convergence of meridians toward the poles,

$$A_{\text{cell}} = (\Delta\phi \Delta\lambda) R^2 \cos \phi, \quad (16)$$



where R is the Earth's radius and $\Delta\phi = \Delta\lambda = 0.5^\circ$ (in radians). The total land-biosphere carbon flux is the area-weighted sum over grid cells; elemental carbon is converted to CO_2 mass with the stoichiometric ratio 44/12 where a CO_2 -mass basis is required (the carbon flux itself is passed to IMOGEN):

$$CO_{2,\text{land}} = \left(\sum_{\text{grid}} F_{\text{net}} \cdot A_{\text{cell}} \right) \times \frac{44}{12}. \quad (17)$$

A positive total denotes a net source to the atmosphere and a negative total a net sink, ensuring that the land-biosphere CO_2 component is harmonised with the land-use trajectories and biophysical constraints of the coupled LandSyMM framework.

2.2.7 Land-biosphere methane (CH_4) fluxes

Land-biosphere methane is simulated by the wetland (LPJ-WHyMe) methane scheme of LPJ-GUESS, applied over the GLWD3-derived wetland area. Boreal and arctic wetlands north of 40°N follow the LPJ-WHyMe (Wetland Hydrology and Methane) parameterisation of Wania et al. (2010), while wetlands below 40°N – including the tropical wetlands that make the largest contribution to the global wetland CH_4 source (Saunio et al., 2025) – follow the complementary formulation of Spahni et al. (2011). The wetland extent on which this scheme operates is delineated from the GLWD3 global wetland dataset (Lehner and Döll, 2004). In our simplified scheme, we aggregate the GLWD3 wetland classes (including bog, fen and mire (peatland in the strict sense)), applying the aggregate class as a fixed fraction carved from the natural land class (Sect. 2.3.3), and held constant in time. Wetland is represented only within the natural land class and is not carried on the managed (cropland or pasture) stands, so no wetland methane is generated where PLUM assigns land to agriculture (methane from rice paddies is instead represented separately by the Tier-1 rice-cultivation module, Sect. 2.2.3). This keeps the source separate from the IPCC Tier-1 agricultural modules and the PLUM land-use categories (Alexander et al., 2018). Because the wetland area is time-invariant, the historical and future wetland CH_4 trajectories reflect climate- and hydrology-driven changes in the per-area flux (including the temperature sensitivity of wetland methanogenesis; Chadburn et al. (2020)). Wetland-area dynamics are not modelled (PLUM does not resolve wetlands), an acknowledged limitation given the real-world sensitivity of wetland extent to hydrological change. Because the peatland-tuned parameterisation is applied over the broader GLWD3 wetland area rather than a peat-soil-only mask, the flux is reported as a wetland CH_4 source and peat-soil extent is not isolated, a further acknowledged simplification (resolving managed-peatland CO_2 and CH_4 fluxes through their empirical dependence on water-table depth (Evans et al., 2021) is a natural future extension). The time-invariant area is a limitation for the area-driven trend rather than for the magnitude of the flux, which is set by the calibrated LPJ-WHyMe/Spahni per-area parameterisation. Wetland-area dynamics under climate change remain an open problem across Earth system models, so our decision to hold the area static is a conservative choice for a process-based estimate. In JULES for instance, the meteorological driving data, as opposed to the choice of wetland-extent configuration, dominate the simulated CH_4 seasonal cycle (Parker et al., 2022). The Global Methane Budget instead prescribes a satellite-derived, monthly-varying wetland extent (WAD2M, covering the period 2000-2020) (Zhang et al., 2021) to remove this source of uncertainty, but it does not extend over the full 1900-2100 horizon required by our coupled



framework. The resulting historical wetland CH₄, together with the prescribed inland-freshwater and reservoir terms, yields an integrated CH₄ budget that reconciles with the Global Methane Budget to within a few per cent and reproduces the observed CH₄ concentration record (Sects. 3.2.1, 3.2.2), indicating that the static-area treatment does not produce an unreasonable total natural source. The framework thus resolves the wetland CH₄ source mechanistically. The remaining natural freshwater CH₄ is not modelled here; it is added when the natural CH₄ budget is assembled for IMOGEN, as the constant inland-freshwater (+112 Tg CH₄ yr⁻¹) and reservoir, dam and canal (-23 Tg CH₄ yr⁻¹) terms of the Global Methane Budget (Saunio et al., 2025) (Sect. 2.4.4). Mineral-soil and tropical mineral-wetland methane dynamics beyond the mapped wetland area are not represented mechanistically given their sensitivity to hydrological change under warming, a further acknowledged limitation.

A fraction of the daily heterotrophic respiration is distributed vertically through the soil column as the substrate for methanogenesis; the methane produced is partly oxidised by methanotrophs in the aerobic upper soil (the “acrotelm”), at a rate that depends on the methane concentration and the water-table-dependent oxygen supply. The net soil-to-atmosphere methane flux is the sum of three mechanistically distinct transport pathways (Wania et al., 2010),

$$F_{\text{CH}_4} = F_{\text{plant}} + F_{\text{ebullition}} + F_{\text{diffusion}}, \quad (18)$$

namely plant-mediated transport through the aerenchyma of vascular plants (bypassing oxidation), ebullition once the dissolved-methane partial pressure exceeds a threshold (15% of atmospheric pressure), and concentration-gradient diffusion through the soil pore space.

LPJ-GUESS reports the methane flux on a carbon-mass basis (g CH₄-C m⁻² month⁻¹). The full methane molecular mass is recovered with the ratio of the molecular weight of methane to that of carbon (16/12),

$$F_{\text{CH}_4(\text{mass})} = F_{\text{CH}_4\text{-C}} \times \frac{16}{12}. \quad (19)$$

The total annual land-biosphere methane flux is obtained by summing the converted monthly fluxes and integrating over the grid-cell area (Eq. 16), with a factor 10⁻¹² converting grams to Teragrams:

$$CH_{4,\text{land}} = \left(\sum_{\text{grid}} \sum_{\text{months}} F_{\text{CH}_4(\text{mass})} \cdot A_{\text{cell}} \right) \times 10^{-12}. \quad (20)$$

2.2.8 Mechanistic land-biosphere nitrous oxide (N₂O) fluxes

Land-biosphere nitrous oxide is simulated by the process-based soil-nitrogen transformation scheme of LPJ-GUESS (Xu-Ri and Prentice, 2008; as implemented by Smith et al., 2014; with subsequent updates following Ma et al., 2022), in which N₂O is released as a by-product of microbial nitrification and denitrification. This process-based term represents the natural and land-use-change-induced soil (and fire) N₂O together with the synthetic-fertiliser-driven cropland soil N₂O, all resolved by the same scheme across the fertilised (cropland) and unfertilised stands. The remaining agricultural managed-soil N₂O (i.e.,



the manure-applied, crop-residue, drained-organic-soil and grazing-deposition sources) is owned by the Tier-1 modules (Sect. 2.2.5), so that each source is represented exactly once (cf. the wetland-methane treatment of Sect. 2.2.7). LPJ-GUESS resolves the mineral-soil nitrification-denitrification response to nitrogen inputs but does not represent the manure-management-system, crop-residue, drained-organic-soil or grazing-deposition activity terms of the Tier-1 inventory, which therefore remain with the
 410 Tier-1 modules. The synthetic-fertiliser cropland flux, which the scheme does resolve on the fertilised stands, is owned by LPJ-GUESS. At the present day the process-based and Tier-1 terms together reconcile to the global N₂O budget (Sect. 3.2.1). The scheme partitions soil mineral nitrogen between aerobic and anaerobic fractions according to the soil moisture (water-filled pore space, f_ω),

$$N_{x, \text{aero}} = N_x (1 - f_\omega), \quad (21)$$

415 $N_{x, \text{anaero}} = N_x f_\omega. \quad (22)$

Nitrification oxidises the aerobic ammonium pool to nitrite and nitrate, releasing a small fraction of the throughput as N₂O. Denitrification (i.e., the dominant N₂O source in wet soils) reduces nitrate stepwise toward N₂, at a rate governed by nitrate and labile-carbon availability, soil temperature, and the anaerobic fraction. As the soil becomes wetter the reduction proceeds further, favouring N₂ over N₂O. In addition, a fixed fraction of the nitrogen volatilised during vegetation fires is emitted as
 420 N₂O (3.6% of fire-emitted N), so that the total land-biosphere N₂O combines soil and fire contributions.

LPJ-GUESS reports the nitrogen-gas fluxes on a nitrogen-atom-mass basis (kg N ha⁻¹ yr⁻¹). The full N₂O molecular mass is recovered with the ratio of the molecular weight of N₂O to that of its two nitrogen atoms (44/28),

$$F_{\text{N}_2\text{O}(\text{mass})} = F_{\text{N}_2\text{O-N}} \times \frac{44}{28}. \quad (23)$$

The total land-biosphere N₂O is then obtained by integrating over the grid-cell area (Eq. 16), with the factor 10⁻⁴ reconciling
 425 the per-hectare flux with the cell area A_{cell} in m² (1 ha = 10⁴ m²) and the factor 10⁻⁹ converting kilograms to Teragrams,

$$N_2O_{\text{land}} = \left(\sum_{\text{grid}} F_{\text{N}_2\text{O}(\text{mass})} \cdot A_{\text{cell}} \right) \times 10^{-4} \times 10^{-9}. \quad (24)$$

2.2.9 Scenario framework and reference emissions

The coupled framework is driven over 1900-2100 by all five SSP-RCP scenarios of the CMIP6 ensemble (i.e., SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0, and SSP5-8.5 (Meinshausen et al., 2020; O'Neill et al., 2016)), spanning the strong-mitigation
 430 to high-forcing range of plausible socioeconomic and emission futures.



The anthropogenic reference for the integrated dataset is the harmonised RCMIP (CMIP6) emission trajectory, into which the bottom-up Tier-1 agricultural CH₄ and N₂O estimates (Sects. 2.2.1-2.2.5) and the LPJ-GUESS land-biosphere CO₂, CH₄ and N₂O fluxes (Sects. 2.2.6-2.2.8) are substituted for the corresponding sectors, with the remaining non-agricultural sectors retained from RCMIP.

435 The assembly, harmonisation, and historical benchmarking of these anthropogenic and natural streams into internally consistent total trajectories are detailed in Sect. 2.3. The resulting emissions drive the IMOGEN climate emulator to generate atmospheric greenhouse-gas concentrations and radiative forcing (Sect. 2.4), which in turn force the trunk LPJ-GUESS ecosystem-state production runs that are the subject of this study.

2.3 Data preprocessing, harmonisation and integration

440 2.3.1 Reference emissions and Tier-1 substitution

The emissions delivered to IMOGEN combine a top-down global reference with the bottom-up estimates developed in Sect. 2.2. The reference is the harmonised RCMIP (CMIP6) emissions dataset (Reduced Complexity Model Intercomparison Project Phase 2; v5.1.0) (Nicholls et al., 2021), which provides globally complete anthropogenic CH₄, N₂O, and CO₂ trajectories for the historical period and for each SSP-RCP scenario. Rather than adopting the RCMIP agricultural emissions, we replace them
445 with our process-based Tier-1 estimates while retaining all other (non-agricultural) sources from RCMIP. For CH₄ and N₂O this is a residual substitution:

$$E_{\text{total}}(t) = [E_{\text{RCMIP}}(t) - E_{\text{RCMIP,agri}}(t)] + E_{\text{model,agri}}(t), \quad (25)$$

where E_{RCMIP} is the RCMIP anthropogenic total, $E_{\text{RCMIP,agri}}$ the RCMIP agricultural component removed to prevent double counting, and $E_{\text{model,agri}}$ the sum of our bottom-up sectors: enteric fermentation, manure management, and rice cultivation for CH₄ (Sects. 2.2.1-2.2.3), and manure management and managed soils excluding synthetic fertiliser for N₂O (Sects. 2.2.4-2.2.5), the synthetic-fertiliser cropland source being supplied instead by the process-based LPJ-GUESS land-biosphere term (Sect. 2.2.8). The agricultural component removed is the RCMIP Agriculture, Forestry and Other Land Use (AFOLU) “Agriculture” sub-sector for CH₄ and the full AFOLU aggregate for N₂O. The non-agricultural background (energy, industry, transport, shipping, waste, and residential sources) is carried unchanged from RCMIP.

455 Carbon dioxide is treated differently, because its land flux is resolved mechanistically. The anthropogenic component is the RCMIP fossil-and-industrial term (E_{FOS}), and the land-atmosphere exchange, including the CO₂ released when natural land is converted to managed use, is supplied directly by LPJ-GUESS as the net land-atmosphere CO₂ flux F_{net} (Sect. 2.2.6), so that the total CO₂ source presented to IMOGEN is

$$E_{\text{CO}_2}(t) = E_{\text{FOS}}(t) + F_{\text{net}}(t). \quad (26)$$



Both terms are summed on a common carbon-mass basis (Pg C yr^{-1} , equivalently Gt C yr^{-1}): F_{net} is already a carbon flux, while the fossil-and-industrial term, supplied by RCMIP in CO_2 mass, is converted to carbon mass by the stoichiometric ratio 12/44, so that the FaIR module receives the combined source directly in carbon units. No Tier-1 substitution is applied to CO_2 : land-use CO_2 is excluded from E_{FOS} and is instead represented within F_{net} , which already embeds the land-use-change and management fluxes (Sect. 2.2.6).

2.3.2 Temporal coverage and stream integration

Each gas is assembled into a continuous 1900-2100 trajectory for every scenario by combining streams of differing temporal coverage (Table 6). The agricultural substitution term $E_{\text{model,agri}}$ follows three regimes: over 1900-1969, before reliable activity data, it defaults to the RCMIP agricultural values (so that $E_{\text{total}} \equiv E_{\text{RCMIP}}$ and no substitution occurs); over 1970-2019 it is the Tier-1 inventory driven by FAO activity data; and from 2020 it is the Tier-1 inventory driven by PLUM scenario activity data. The land-biosphere LPJ-GUESS fluxes use a single shared historical trajectory (1901-2020, with the 1900 value set equal to 1901) and scenario-specific trajectories from 2021, while the RCMIP reference is common across scenarios through 2014 and diverges by SSP-RCP from 2015.

Because the historical and scenario streams are produced by different methods and activity data, small discontinuities arise in the anthropogenic emissions at the 2019/2020 transition from FAO- to PLUM-driven agriculture. The agricultural CH_4 total steps by approximately -5% (reflecting the change in activity-data source), and the agricultural N_2O total by approximately +14% (additionally reflecting the manure-management parameter update from the 2006 Guidelines to the 2019 Refinement at the historical/scenario boundary). The anthropogenic CO_2 series shows no such step, as it is the uninterrupted RCMIP fossil-and-industrial trajectory with no Tier-1 substitution; interannual variability in the CO_2 total instead reflects the land-atmosphere flux (Sect. 2.2.6). These steps are retained in the emissions handed to IMOGEN, so that the forcing reflects the genuine methodological transition. The only smoothing applied in the framework is a centred running mean used for figures and for the reference series (Sect. 2.3.4). The integrated emissions are shown both raw (annual) and as the 10-year running mean in Supplement Fig. S27, making the retained transition steps and the figure smoothing explicit.

Table 6. Data sources, temporal coverage, and modelling status by emission category.

Emission category	Modelling approach	Data source	Coverage
Non-agricultural anthropogenic (energy, industry, transport, shipping, waste, residential)	Prescribed (background)	RCMIP (CMIP6)	1900-2100
Agriculture (livestock, rice, fertiliser)	Modelled (IPCC Tier-1)	RCMIP (1900-1969) / FAO (1970-2019) / PLUM (2020-2100)	1900-2100



Emission category	Modelling approach	Data source	Coverage
Wetland & high-latitude CH ₄	Modelled (LPJ-GUESS wetland/LPJ-WHyMe scheme)	Internal simulation	1901-2100
Land-biosphere soil & fire N ₂ O	Modelled (LPJ-GUESS)	Internal simulation	1901-2100
Ocean & non-land natural N ₂ O	Prescribed (natural baseline)	FaIR-ERF v1.3 (Smith et al., 2018)	1900-2100 (constant after 2005)
Land-biosphere CO ₂ (net land-atmosphere flux, incl. land-use change)	Modelled (LPJ-GUESS)	Internal simulation	1901-2100

2.3.3 Land-use harmonisation

485 The land-use forcing for the LPJ-GUESS simulations – both the ISIMIP-3b prescribed-climate runs and the IMOGEN-coupled
 production runs – is harmonised across the historical-scenario boundary following the LandSyMM land-use harmonisation
 procedure of Rabin et al. (2020), an adaptation of the Land-Use Harmonisation framework (LUH1/LUH2) (Hurtt et al., 2011;
 Hurtt et al., 2020). Harmonisation is required because the PLUM land-use fractions at the start of the scenario period do not
 exactly match the historical land-use end-state used to initialise LPJ-GUESS. Feeding the raw PLUM fractions directly would
 490 generate artefactual single-year abandonment or expansion pulses that distort the carbon-cycle response.

The historical baseline is derived from the HILDA+ (Historic Land Dynamics Assessment) v2 dataset (Winkler et al., 2021),
 remapped to the 0.5° HILDA+ remap grid (62,892 land cells; the ecosystem simulations are run on the climate- and land-
 use-complete subset of 62,512 cells) over 1901-2020 and resolved into four land-use classes (i.e., cropland, pasture, natural,
 and barren) with HILDA+ forest classes folded into natural and urban into barren. From the 2020 baseline, the harmonisation
 495 applies PLUM's projected **net** annual area changes (as with the HILDA+ historical baseline, gross transitions are not used),
 computed at 2° resolution and redistributed to 0.5°: the agricultural-class deltas are added to the harmonised state and the
 natural class absorbs the residual change. Where a cell cannot accommodate the change – owing to protected areas, steep
 terrain, or a minimum natural-vegetation reserve – it is redistributed to neighbouring cells, conserving global totals where
 possible. The harmonised fractions for 2021-2100 thereafter follow PLUM's projected trajectory, and the resulting land-cover,
 500 crop-fraction, nitrogen-fertiliser, and irrigation fields constitute the LPJ-GUESS land-use forcing. The resulting global land-
 cover-area trajectories and end-of-century distributions are shown in Supplement Figs. S22 and S23.

For the methane-enabled configuration (Sect. 2.2.7), a fifth class, wetland, is introduced in a post-processing step from the
 GLWD3 global wetland dataset (Lehner and Döll, 2004), taken as the aggregate of the GLWD3 wetland classes. To remain
 compatible with the area-conserving harmonisation, the wetland fraction of each grid cell is held time-invariant and carved
 505 from the natural class:



$$f_{\text{wet}} = \min\left(\min_t f_{\text{nat}}(t), f_{\text{GLWD3}}\right), \quad f'_{\text{nat}}(t) = f_{\text{nat}}(t) - f_{\text{wet}}, \quad (27)$$

so that wetland never exceeds the natural area available in any year and the five fractions sum to unity at every cell and year. Gross land-use transitions and an explicit managed/unmanaged forest split are planned extensions and are not part of the configuration used here.

510 2.3.4 Historical benchmarking and reference series

The integrated historical emissions are benchmarked against the observationally constrained global budgets on a per-gas basis: the Global Methane Budget (GMB) (Saunio et al., 2025) for CH₄, the Global Nitrous Oxide Budget (GNB) (Tian et al., 2024) for N₂O, and the Global Carbon Budget (GCB) (Friedlingstein et al., 2025) for CO₂, each over its observational period. Two reference series are constructed: a scenario-baseline reference built from the RCMIP trajectory plus a FaIR natural baseline
 515 (Option A), retained as a supplementary diagnostic; and an observation-anchored reference (Option B, the primary reference) that anchors the historical period to the observational budgets, and follows the scenario-baseline series outside the anchored window. The latter is a bias correction of the reference toward the observed budgets over the historical window. For CO₂, because the model's total ($E_{\text{FOS}} + F_{\text{net}}$) carries the land flux explicitly and the budget's fossil term does not, the observation-anchored reference adds back the Global Carbon Budget land sink (SLAND, of order 2-3 Pg C yr⁻¹ at the present day), so that
 520 reference and model represent the atmospheric CO₂ source on the same basis.

2.4 Coupled model framework: architecture, dataflow and configuration

This section details the coupled architecture, dataflow, and configuration of the framework summarised schematically in Fig. 1 (Sect. 2.1).

2.4.1 Architectural overview and control layer

525 Coupling is orchestrated by a dedicated Intermediary Controller (IC), implemented as a reproducible workflow layer that (i) sequences component model execution, (ii) standardises spatial/temporal grids and metadata, (iii) constructs a sector-complete integrated emissions dataset, and (iv) reports the methodological discontinuities at the historical/scenario phase boundaries, which are retained in the driving emissions (Sect. 2.3.2). The IC interfaces with four functional blocks, each with a defined coupling role:

- 530 1. IMOGEN (coupling role: climate emulator): receives the annual integrated emissions time series $E_g^{\text{integrated}}(t)$ from the IC and returns (i) annual atmospheric GHG concentration trajectories via the FaIR effective radiative forcing (ERF) and (ii) monthly gridded climate fields via pattern scaling of the global land temperature anomaly (see Appendix B3).
2. LPJ-GUESS (coupling role: dual – biophysical constraint provider in Stage I; ecosystem response simulator in Stage II): provides annually aggregated potential yield tables to PLUM in Stage I; receives annual PLUM LUM forcings and



- 535 monthly IMOGEN climate fields to simulate realised ecosystem carbon, nitrogen, and yield trajectories in Stage II (see Appendix B1).
3. PLUM v2 (coupling role: land-use and activity data provider): receives 5-year mean potential yields from LPJ-GUESS and SSP socioeconomic drivers to produce annual land-use, management intensity, and livestock population outputs used as activity data for the IPCC emission modules and as LUM forcings for Stage II LPJ-GUESS (see Appendix B2).
- 540 4. Agricultural emissions module – IPCC 2019 Tier-1 (coupling role: agricultural GHG accounting): receives PLUM (scenario) or FAO (historical) activity data and returns annual mass-based CH₄ and N₂O emission estimates for the source categories not represented mechanistically in LPJ-GUESS (enteric fermentation, manure management, rice cultivation, managed soils; see Sect. 2.2).

2.4.2 Coupling semantics and cadence

- 545 The coupling is annual at the system boundary, with sub-annual dynamics resolved internally by component models:
- LPJ-GUESS resolves physiological and hydrological processes at daily timesteps and produces annual diagnostics/fluxes for coupling.
 - IMOGEN produces monthly climate fields for each simulation year from annually evolving forcing. Patterns are derived by regressions of each climate variable against global land temperature anomaly (Huntingford et al., 2010).
 - 550 – PLUM updates land use/management and livestock activity annually, using 5-year averaged potential yields as biophysical constraints (Alexander et al., 2018).

All inter-module exchanges are performed on a common $0.5^\circ \times 0.5^\circ$ global grid (consistent with standard LandSyMM deployments) (Table 7), and the IC ensures gridded remapping/aggregation where internal grids differ.

Table 7. Coupling interfaces and exchanged variables.

Interface	Producer -> Consumer	Variable(s)	Units / format	Aggregation	Notes
Climate forcing	IMOGEN -> LPJ-GUESS	air temperature, precipitation, shortwave & longwave radiation, humidity, wind, wet days	0.5° gridded (K; mm; W m^{-2} ; %; m s^{-1} ; counts)	monthly	Pattern-scaling regressions against the global land-temperature anomaly (Huntingford et al., 2010).



Interface	Producer -> Consumer	Variable(s)	Units / format	Aggregation	Notes
Yield (productivity) constraint	LPJ-GUESS -> PLUM	crop (CFT) and pasture productivity (NPP)	0.5° gridded (kg DM ha ⁻¹ yr ⁻¹ ; kg C yr ⁻¹)	5-year mean	Factorial management matrix: fertiliser 0/200/1000 kg N ha ⁻¹ ; rainfed vs fully irrigated (Rabin et al., 2020).
Land-use & management forcing	PLUM -> LPJ-GUESS	crop/pasture area fractions, irrigation intensity, fertiliser rate	0.5° gridded fractions & rates (e.g. kg N ha ⁻¹ yr ⁻¹)	annual	Harmonised at the HILDA+ (Winkler et al., 2021) historical -> PLUM scenario boundary via a LUH-style routine (Hurtt et al., 2011; Rabin et al., 2020); Sect. 2.3.3.
Agricultural activity for inventory	PLUM/FAO -> IPCC Tier-1	livestock (by type), rice area, fertiliser/manure inputs	country-level counts/areas, grid-mapped to 0.5°	annual	Activity drivers switch from FAO (historical) to PLUM (scenario).
Bottom-up land fluxes	LPJ-GUESS -> IC	CO ₂ net land-atmosphere flux, land-biosphere CH ₄ (wetland), soil & fire N ₂ O	0.5° gridded fluxes (kg m ⁻² yr ⁻¹) -> mass	annual	Converted to mass by grid-cell-area integration (Sects. 2.2.6-2.2.8).



Interface	Producer -> Consumer	Variable(s)	Units / format	Aggregation	Notes
Integrated emissions	IC -> IMOGEN	$E_g^{\text{integrated}}(t), g \in \{\text{CO}_2, \text{CH}_4, \text{N}_2\text{O}\}$	Tg yr ⁻¹ (global totals)	annual	Built via sector-ownership + residualisation (Sect. 2.4.4); the 1970/2020 boundary discontinuities are retained, not smoothed (Sect. 2.3.2).

555 PLUM's dependency on climate-sensitive productivity is handled using potential-yield tables from LPJ-GUESS averaged over multi-year windows (5-year means), which reduces sensitivity to interannual noise in yields passed to the economic optimiser. Pasture productivity is represented as the annual net primary productivity (NPP) of the managed pasture stands. Rice yield potentials are included to provide PLUM with biophysical constraints on irrigated rice area allocation, which directly drives the rice CH₄ emission module (Sect. 2.2.3).

560 Future simulations are performed for the five SSP-RCP scenarios introduced in Sect. 2.2.9. IMOGEN is forced by the corresponding annual emissions for each GHG and returns both atmospheric concentrations and climate.

2.4.3 Two-stage coupling protocol

To resolve the dependency of land-use decisions on climate-dependent yield potentials while still representing the emissions-climate feedback, the system is executed as a two-stage, sequentially coupled protocol (Fig. 1).

565 Stage I (baseline climate - yield potentials - open loop)

To provide PLUM with the biophysical yield constraints it uses to allocate agricultural production, we run LPJ-GUESS simulations spanning 1850-2100 with prescribed ISIMIP-3b (Lange, 2019; Lange and Büchner, 2021) (MRI-ESM2-0 GCM; Yukimoto et al. (2019)) bias-corrected forcings (the ISIMIP-3b historical period runs to 2014 and the SSP-RCP scenario period from 2015; e.g., mean, minimum, and maximum near-surface air temperature, shortwave radiation, precipitation, nitrogen
 570 deposition, atmospheric CO₂ concentration) at 0.5° resolution. LPJ-GUESS computes gridded biophysically-derived yield potentials for crop functional types (e.g., winter and spring C3 cereals, C4 cereals, pulses, and rice) under a factorial management matrix (fertiliser rates 0, 200, 1000 kg N ha⁻¹; rainfed vs. fully irrigated) and pasture productivity as the corresponding annual net primary productivity (NPP). PLUM interpolates between the three factorial fertiliser levels using the diminishing-returns response function described in Alexander et al. (2018), fitting a smooth yield-nitrogen curve to the three LPJ-GUESS factorial



575 points for each grid cell, CFT, and irrigation class. This ensures that continuous gradients of fertiliser application projected by PLUM map onto physiologically realistic yield responses at intermediate nitrogen rates. Potential yields are averaged over rolling 5-year windows and passed to PLUM. This reproduces the established LandSyMM workflow (Rabin et al., 2020).

Stage II (integrated emissions - feedback climate - realised ecosystem state - coupled, sequential)

580 PLUM ingests the potential yields and SSP socioeconomic drivers to generate annual trajectories of cropland/pasture area fractions, crop allocation, fertiliser and irrigation intensities, and livestock populations. These outputs form (i) the land-use/management forcing for a realised LPJ-GUESS run, and (ii) the activity drivers for the inventory emissions module. The IC then constructs an integrated emissions dataset by combining bottom-up modelled components with residual “background” emissions retained from the RCMIP (CMIP6) dataset (Sect. 2.4.4). This integrated emissions dataset forces IMOGEN to emulate the feedback-adjusted climate, which is then used to drive a final LPJ-GUESS simulation in which potential-yield mode
 585 is disabled and realised ecosystem trajectories are simulated under harmonised land use and feedback climate. For the Stage II coupled run, IMOGEN applies the pattern-scaled climate anomaly derived from a CMIP6 MRI-ESM2-0 pattern set, obtained by regressing the local monthly climate fields on the global-mean land-temperature anomaly of the MRI-ESM2-0 simulation following the standard IMOGEN pattern-scaling methodology (Huntingford et al., 2010; Zelazowski et al., 2018) (rather than adopting one of the published pattern sets – the 22-GCM CMIP3-generation set of Zelazowski et al. (2018) or the 34-model
 590 CMIP5 set of Comyn-Platt et al. (2018)). This bespoke CMIP6 pattern set and its matching energy-balance-model parameters were derived for the CMIP6 ensemble by G. Munday (Mathison et al., 2025). The global-mean temperature response that scales these patterns is governed by the embedded two-box energy-balance model (Forster et al., 2021), whose parameters are calibrated to the same MRI-ESM2-0 simulation (inverse climate-sensitivity parameters of 1.5 and 1.3 W m⁻² K⁻¹ for the land and ocean, respectively), and driven by the FaIR effective radiative forcing. FaIR also supplies the emissions-to-concentration
 595 gas cycle, including the atmospheric lifetimes (sinks) of CH₄ and N₂O. The pattern-scaled monthly anomalies are superimposed on an observation-based baseline climatology – the 1960-1989 monthly means of the CRU-JRA v2.4 reanalysis (the direct successor to the CRUNCEP product), which supplies near-surface temperature, precipitation, shortwave and longwave radiation, diurnal temperature range, relative humidity, wind speed and surface pressure on the coupling grid. The climate handed to LPJ-GUESS is therefore this observed baseline plus the emulated anomaly. The difference between this observa-
 600 tional baseline and the ISIMIP-3b reference mean state is the origin of the residual mean-state difference between the coupled and prescribed climates reported in Sect. 3.3. This difference is largely regional and near-neutral in the global mean. Referencing the anomalies to an observed baseline is a bias-correction step directly analogous to the construction of the ISIMIP-3b reference itself, whose MRI-ESM2-0 fields are bias-adjusted to the W5E5 v2.0 observational dataset over the 1979-2014 reference period (Lange, 2019; Lange and Büchner, 2021). Both configurations are therefore anchored to observations, and the
 605 residual regional mean-state difference between them is the difference between two observation-based baseline climatologies (i.e., the IMOGEN emulator’s CRU-JRA baseline and the W5E5-anchored ISIMIP-3b reference). This gives the land model physically realistic absolute fields, at the cost of that residual regional difference. We retain this observation-based baseline, report the difference (Sect. 3.3), and isolate the emission-pathway feedback with the identical-emulator diagnostic (Sect. 2.4.6), which is unaffected by the baseline choice. Both the spatial patterns and the global-mean energy-balance response are therefore



610 MRI-ESM2-0-based, and the same MRI-ESM2-0 GCM underlies the ISIMIP-3b reference climate (Sect. 2.4.6). This ensures that the coupled-versus-prescribed comparison (Sect. 3.3-3.4) is not confounded by GCM identity. The sensitivity of Stage II results to GCM pattern choice is not explored in the present paper but represents a natural direction for ensemble uncertainty analysis in future work.

Prior to the transient Stage I simulation, LPJ-GUESS undergoes a soil carbon and nitrogen spin-up phase in which the model
 615 is run under repeated pre-industrial climate (here, the mean 1850-1900 climatology from the ISIMIP-3b MRI-ESM2-0 forcing dataset) until all soil organic matter (SOM) pools reach a steady state, defined as interannual variation in global total soil carbon of less than 0.1 Pg C yr⁻¹. This typically requires 500 simulation years. The spin-up phase uses pre-industrial atmospheric CO₂ concentrations (approximately 285 ppm) and pre-industrial nitrogen deposition fields, consistent with the 1850 initial conditions of the transient simulation. Natural vegetation cover is prescribed according to the LPJ-GUESS potential natural
 620 vegetation algorithm during spin-up. The equilibrated soil carbon and nitrogen states at the end of the spin-up serve as initial conditions for the 1850 start of the transient Stage I simulation. The coupled (IMOGEN-driven) configuration used in the Tier-3 comparison (Sect. 2.4.6) performs the same 500-year spin-up procedure, but under its own emulated climate, whose anomalies are referenced to the emulator's CRU-JRA baseline climatology (Sect. 2.4) rather than to the ISIMIP-3b MRI-ESM2-0 mean state. The two configurations therefore equilibrate to different baseline climatologies, which is the origin of the
 625 persistent, roughly forcing-independent difference in absolute carbon and nitrogen pools present from the start of the coupled and prescribed transient simulations (Sect. 3.4.1).

2.4.4 Emissions integration, sector ownership and avoidance of double counting

A core requirement is that the emissions time series supplied to IMOGEN be both *sector-complete* (covering all anthropogenic and land-biosphere sources IMOGEN requires) and *non-overlapping* (each source represented exactly once). The IC enforces
 630 this through a sector-ownership rule and residualisation procedure (Table 8): for each gas $g \in \{\text{CO}_2, \text{CH}_4, \text{N}_2\text{O}\}$ and year t ,

$$E_g^{\text{integrated}}(t) = E_g^{\text{residual}}(t) + E_g^{\text{LPJG}}(t) + E_g^{\text{IPCC}}(t), \quad (28)$$

where E_g^{LPJG} are the process-based land-biosphere fluxes from LPJ-GUESS (net land CO₂, land-biosphere CH₄, and soil and fire N₂O including the synthetic-fertiliser cropland response; Sects. 2.2.6-2.2.8, after grid-area integration), E_g^{IPCC} the Tier-1 agricultural CH₄ and N₂O – the latter excluding synthetic fertiliser, which is owned by the LPJ-GUESS term – computed
 635 from PLUM (scenario) or FAO (historical) activity data (Sects. 2.2.1-2.2.5), and E_g^{residual} the RCMIP (CMIP6) emissions remaining once the AFOLU components replaced by the LPJ-GUESS and Tier-1 terms have been removed – guaranteeing one-to-one sector ownership and preventing double counting. Equation (28) is the coupling-level expression of the residual substitution defined in Sect. 2.3.1.

Sector ownership is segmented in time according to activity-data availability, following the 1900-1969 (RCMIP-only), 1970-
 640 2019 (FAO-driven) and 2020-2100 (PLUM-driven) regimes of Sect. 2.3.2. At each year the IC performs unit harmonisation and area-weighted aggregation of the gridded LPJ-GUESS fluxes and the activity-based agricultural emissions to annual global



totals by gas, yielding the sector-complete $E_g^{\text{integrated}}(t)$ supplied to IMOGEN. The methodological discontinuities that arise at the 1970 and 2020 ownership interfaces (Sect. 2.3.2) are retained in this forcing.

For CH_4 , the LPJ-GUESS land-biosphere term $E_{\text{CH}_4}^{\text{LPJG}}$ resolves only the wetland source, on the time-invariant wetland mask (Sect. 2.2.7). The remaining natural freshwater CH_4 is completed by adding the constant inland-freshwater (+112 Tg CH_4 yr⁻¹) and reservoir, dam and canal (-23 Tg CH_4 yr⁻¹) terms of the Global Methane Budget (Saunois et al., 2025), enabling the natural CH_4 supplied to IMOGEN to approximate the complete natural source.

For N_2O specifically, the natural source requires one further term. The IMOGEN/FaIR concentration budget carries no internal natural-source reservoir, so the *complete* natural N_2O must be delivered through the input emissions. The LPJ-GUESS land-biosphere term $E_{\text{N}_2\text{O}}^{\text{LPJG}}$ (soil plus fire) is a land-only quantity and omits the ocean and other non-land natural N_2O ($\approx$ 3-6 Tg N_2O yr⁻¹ of the $\approx$ 14-17 Tg yr⁻¹ total natural budget) (Tian et al., 2024). The integrated N_2O therefore adds a prescribed ocean and non-land natural baseline (i.e., the FaIR-ERF v1.3 natural-emissions baseline (Smith et al., 2018)) to the land-biosphere flux. The budget is therefore driven by the full natural source consistent with the prescribed CMIP6 non- CO_2 radiative forcing (Table 8). The consequences of this choice for the prognostic N_2O concentration are evaluated in Sect. 3.2.2 and discussed in Sect. 4.3.

Table 8. Emissions sector-ownership and residualisation rules (source category, owning component, and treatment).

Emissions component	Gas(es)	Ownership in LandSyMM	Data / method	Treatment in integrated dataset
Enteric fermentation	CH_4	IPCC module (activity-driven)	FAO (historical) / PLUM (scenario) activity + IPCC 2019 EFs	Replaces the corresponding AFOLU component in the RCMIP total; removed from the residual
Manure management	CH_4 , N_2O	IPCC module (activity-driven)	FAO/PLUM activity + IPCC 2019 EFs	as above
Rice cultivation	CH_4	IPCC module (activity-driven)	rice area (FAO historical; PLUM scenario) + IPCC 2019 EFs	as above



Emissions component	Gas(es)	Ownership in LandSyMM	Data / method	Treatment in integrated dataset
Managed soils excl. synthetic fertiliser (manure applied, crop residues, grazing/PRP, drained organic soils, indirect)	N ₂ O	IPCC module (activity-driven)	FAO/PLUM manure, residue & grazing inputs + IPCC 2019 EFs	Replaces the corresponding AFOLU component in the RCMIP total; the synthetic-fertiliser cropland soil N ₂ O is instead supplied by the LPJ-GUESS land-biosphere term
Land-use change / deforestation	CO ₂	LPJ-GUESS (process-based)	LPJ-GUESS land-use change & disturbance	Supplied by LPJ-GUESS as the land-atmosphere flux; the RCMIP CO ₂ series is fossil-and-industrial only, so land CO ₂ is not double-counted
Grassland/savannah & fire emissions	CO ₂ (+ land-biosphere CH ₄ , N ₂ O)	LPJ-GUESS (process-based)	LPJ-GUESS fire module	Included as a modelled land-flux component
Ocean & non-land natural N ₂ O	N ₂ O	Prescribed natural baseline	FaIR-ERF v1.3 natural baseline (Smith et al., 2018)	Added to the LPJ-GUESS land-biosphere N ₂ O to supply the emulator's complete natural source (the FaIR budget has no internal natural term; Sect. 2.4.4)



Emissions component	Gas(es)	Ownership in LandSyMM	Data / method	Treatment in integrated dataset
Non-AFOLU background (industry, power, surface transport, shipping, waste, residential & commercial)	CO ₂ / CH ₄ / N ₂ O	Residual RCMIP (CMIP6)	RCMIP (CMIP6) inventory	Retained unchanged as the residual background

2.4.5 Output products and coupling diagnostics

The coupled workflow produces three families of output: (i) the integrated emissions time series by gas and sector-ownership class (modelled and residual; Sect. 2.4.4); (ii) the IMOGEN-derived atmospheric GHG concentration and climate-forcing trajectories; and (iii) the LPJ-GUESS ecosystem-response variables (i.e., soil and vegetation carbon and nitrogen pools and fluxes, net primary production, and crop yields) from both the prescribed-climate (ISIMIP-3b) run and the feedback-climate coupled (IMOGEN) run. The difference between the two runs forms the principal coupling diagnostic, combining the bottom-up emission-pathway signal with the emulator's mean-state offset relative to the reference. The two are separated by the identical-emulator diagnostic (Sects. 2.4.6, 4.4).

One structural feature of the agricultural modules bears on the interpretation of these outputs: the IPCC Tier-1 physiological and management parameters (typical animal mass, excretion rates, and AWMS fractions; Sects. 2.2.1-2.2.5) are held at their regional defaults throughout 2020-2100. Emission responses to changing herd size, crop area, and fertiliser application are thus captured dynamically through the PLUM activity data, whereas changes in per-head emission intensity arising from future shifts in breed efficiency, diet, or waste-management technology are not represented. This limitation is discussed further in Sect. 4.3. The regional livestock and management parameter values underlying these modules are tabulated in Appendix A.

2.4.6 Output analysis and evaluation

The evaluation of LandSyMM addresses the objectives of Sect. 1 – historical evaluation and benchmark comparison – across three diagnostic tiers.

Tier-1 – Historical agricultural-emission evaluation (1970-2020). The bottom-up Tier-1 emission modules, driven by FAO historical activity data, are compared against two independent references for each modelled source category (i.e., enteric-fermentation CH₄, manure-management CH₄ and N₂O, rice-cultivation CH₄, and managed-soil N₂O) at global and regional aggregation. The references are the FAOSTAT national agricultural-emission inventories and the EDGAR 2025-release gridded sectoral composites (Crippa et al., 2025). Performance is quantified with the root-mean-square deviation (RMSD) and the percentage bias (PBIAS) (Moriassi et al., 2007),



$$\text{PBIAS}(\%) = \frac{\sum_i (E_{\text{mod},i} - E_{\text{obs},i})}{\sum_i E_{\text{obs},i}} \times 100, \quad (29)$$

summed over all years i in the evaluation period (positive PBIAS denotes model over-estimation). We adopt $|\text{PBIAS}| \leq 20\%$ at the global aggregate as the benchmark for the Tier-1 inventory estimates. This reflects the $\approx \pm 10\text{-}20\%$ aggregate uncertainty that remains once the $\pm 20\text{-}50\%$ source-level Tier-1 emission-factor uncertainties (IPCC, 2019) partially cancel across regions and categories, while individual source categories still carry the full $\pm 20\text{-}50\%$ uncertainty. Comparable benchmarks are used in prior global agricultural-GHG inventory studies (Tubiello et al., 2013; Wolf et al., 2017). The root-mean-square deviation is

$$\text{RMSD} = \sqrt{\frac{1}{N} \sum_i (E_{\text{mod},i} - E_{\text{obs},i})^2}, \quad (30)$$

with N the number of years in the evaluation period. It is reported in native emission units and, for the concentration trajectories (Sect. 3.2.2), in ppm or ppb, and is additionally expressed relative to the interannual standard deviation of the reference product.

Tier-2 – Integrated emissions and concentration trajectories (1900-2100). We compare (i) the integrated annual global emissions by gas (CO_2 , CH_4 , N_2O) against the five RCMIP (CMIP6) SSP-RCP reference trajectories and the present-day observational budgets (GMB, GNB, GCB), and (ii) the IMOGEN-derived atmospheric concentrations against the observational record (the EPA Climate-Indicators compilation (U.S. Environmental Protection Agency, 2024) of the NOAA/GML and AGAGE instrumental series, extended back with the Law Dome ice-core record (MacFarling Meure et al., 2006)) over the period of overlap. We do not benchmark the concentrations against the prescribed CMIP6/RCMIP concentration product, since that comparison would largely re-test the FaIR module rather than the coupled system. Acceptable performance is taken as $|\text{PBIAS}| \leq 20\%$ for the integrated emissions and concentration RMSDs of ≤ 10 ppm (CO_2), ≤ 100 ppb (CH_4), and ≤ 15 ppb (N_2O) against the observed record. These bounds are scaled to the relevant uncertainties – the CMIP6 inter-model concentration spread (Meinshausen et al., 2020), the carbon-cycle and pattern-scaling uncertainty propagated through FaIR (Zelazowski et al., 2018), and the observed interannual variability (Saunio et al., 2020). They are benchmarks appropriate to a reduced-complexity prognostic emulator, and departures beyond them are reported as model biases rather than treated as failures.

Tier-3 – Climate-forcing and ecosystem-response differences. To quantify how faithfully the coupled framework reproduces the reference climate and how the resulting feedback climate propagates into ecosystems, we map spatiotemporal differences in (i) the IMOGEN climate fields (near-surface temperature, precipitation, shortwave radiation) between the IMOGEN-coupled run and the ISIMIP-3b (MRI-ESM2-0) reference climate (an evaluation of the pattern-scaled emulator’s fidelity under the integrated forcing), and (ii) the LPJ-GUESS ecosystem-state variables (soil and vegetation carbon and nitrogen pools and fluxes, NPP, crop yields) between the coupled (IMOGEN-driven) feedback climate and the ISIMIP-3b reference climate. Because both the IMOGEN pattern and the ISIMIP-3b reference derive from the same GCM (MRI-ESM2-0; Sect. 2.4), these differences reflect the combined effect of the pattern-scaling emulation and the integrated forcing rather than a



mismatch in GCM identity. A controlled attribution of the emission-pathway effect alone is provided at the climate level by an identical-emulator diagnostic: the IMOGEN engine is run twice under an identical emulator - once forced by the framework's integrated emissions and once by the unmodified RCMIP (i.e., anthropogenic) plus FaIR (i.e., natural) emissions - with the pattern, energy-balance calibration, and all other inputs held fixed and both runs referenced to the same baseline climatology.

715 Because both runs use the identical emulator and the same baseline climatology, the emulator structure and the baseline cancel between them, leaving the difference between the two runs as the emission-pathway signal alone. It is run for the bracketing scenarios (SSP1-2.6 and SSP5-8.5) over the three analysis windows. The result is reported in Sect. 3.3.1 (Fig. S19, Table S6) and interpreted in Sect. 4.4, and the corresponding ecosystem-level partition is deferred to future work. Difference statistics (RMSD and PBIAS) are computed over three windows for each scenario: the scenario-overlap window (2015-2020), mid-

720 century (2040-2060), and the end of century (2080-2100). The spatial fidelity of the emulated climate fields is additionally summarised on Taylor diagrams (Fig. 5), using the centred spatial pattern correlation between the coupled and reference fields and the normalised standard deviation (the ratio of the coupled to the reference spatial standard deviation), both evaluated across all land grid cells. A pattern correlation approaching unity and a normalised standard deviation near one together indicate faithful reproduction of the reference spatial structure and variance. All Tier-3 global statistics (i.e., the global-mean bias

725 and RMSD as well as the spatial pattern correlation and standard-deviation ratio) are cosine-latitude (gridcell-area) weighted, so they are area means over the 0.5° land field rather than equal-per-cell averages.

3 Results

3.1 Historical agricultural-emission evaluation (1970-2020)

We evaluate the bottom-up Tier-1 agricultural-emission modules over 1970-2020 against the FAOSTAT (FAO, 2023) and

730 EDGAR 2025 (Crippa et al., 2025) reference inventories (PBIAS, Eq. 29; Table 9, Fig. 2). For this evaluation the Tier-1 estimate is driven by FAO activity data across the full 1970-2020 window, one year beyond the 2019/2020 FAO-to-PLUM hand-off used to assemble the integrated forcing (Sect. 2.3.2). For manure-management N_2O the historical estimate uses the 2006 IPCC Guidelines emission factors (consistent with FAOSTAT); the 2019 Refinement factors used for the scenario period (Sect. 2.2.4) produce the small step at the 2020 boundary.

735 The two livestock methane modules reproduce the inventory trajectories but sit systematically above them, while rice cultivation sits modestly below. Enteric fermentation, the largest agricultural CH_4 source, is the most strongly biased, exceeding FAOSTAT by 26.6% (EDGAR by 23.1%); manure-management CH_4 is +18.8% relative to FAOSTAT but within 1% of EDGAR (-0.5%); and rice cultivation is -11.3% (FAOSTAT) and -15.7% (EDGAR), the irrigated-rice organic-amendment factor being applied in the summed IPCC form (Sect. 2.2.3). The agricultural CH_4 total is +19.0% relative to FAOSTAT and +13.7%

740 relative to EDGAR over the period, reaching $166.9 \text{ Tg } CH_4 \text{ yr}^{-1}$ in 2020 (FAOSTAT 136.4; EDGAR 148.0). The aggregate high bias is driven by the two livestock sources and is of consistent sign against both independent inventories, indicating a genuine methodological offset, in which the IPCC regional default emission factors exceed the country-specific values under-

lying FAOSTAT and EDGAR. Every source category falls within the ± 20 -50% uncertainty that the IPCC assigns to individual Tier-1 default emission factors (IPCC, 2019).

745 The nitrous-oxide modules agree more closely with the reference inventories than the methane modules. Managed-soil N_2O is -8.3% relative to FAOSTAT (+3.4% vs EDGAR), and manure-management N_2O is +29.0% relative to FAOSTAT on the 2006-Guidelines basis (the scenario-period 2019 Refinement factors are substantially higher). The much larger manure-management N_2O bias against EDGAR (+86.7%; Table 9) reflects EDGAR's substantially lower manure-management N_2O than FAOSTAT, indicating a divergence between the two reference inventories themselves in how manure- N_2O is allocated and
 750 which emission factors are applied. This bears on only the smaller of the two N_2O source categories. The agricultural N_2O total is therefore near-balanced against FAOSTAT and modestly high against EDGAR, of order 7 Tg N_2O yr^{-1} in 2020.

Overall, the bottom-up estimates lie within the Tier-1 uncertainty envelope: the N_2O aggregate and managed soils agree with the established inventories to within the $\pm 20\%$ global-aggregate benchmark, while the agricultural CH_4 aggregate (+19%) sits just within it, at its upper edge, and the individual CH_4 sources (-16 to +27%) remain within this ± 20 -50% per-category uncertainty of the Tier-1 default factors (IPCC, 2019), the aggregate high bias owing to the use of IPCC default rather than nationally
 755 tuned emission factors for the two dominant livestock sources. Although the two inventories are not fully independent, as both rest on IPCC methodology and partly shared activity data, their consistent agreement with the bottom-up estimates establishes the modules as consistent with community estimates and suitable for their intended use in driving the integrated framework (Sect. 3.2).

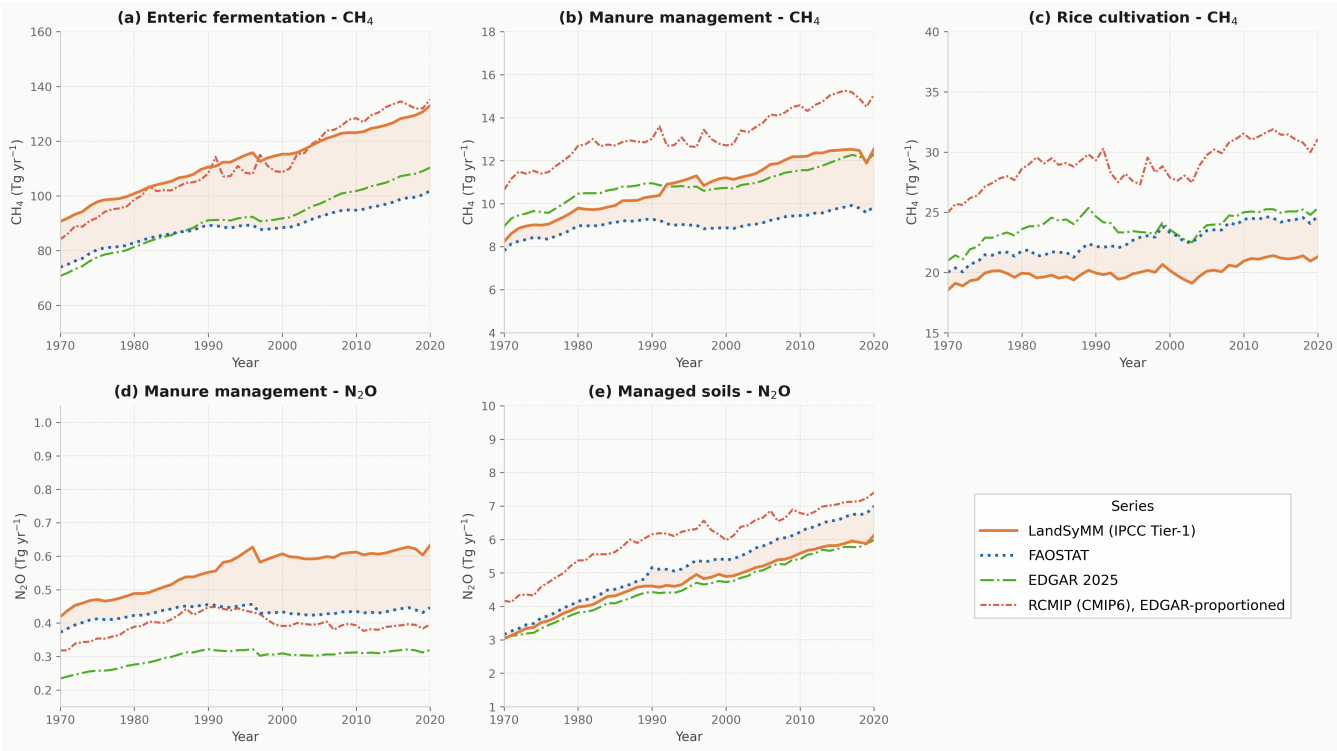
760 **Table 9.** Historical agricultural-emission evaluation: 2020 global totals (Tg yr^{-1} , of the row gas) and percentage bias (PBIAS, 1970-2020) of the LandSyMM bottom-up Tier-1 estimates against the FAOSTAT and EDGAR 2025 inventories, by source category.

Source category (gas)	LandSyMM 2020	FAOSTAT 2020	EDGAR 2020	PBIAS vs FAOSTAT	PBIAS vs EDGAR
Enteric fermentation (CH_4)	133.0	101.9	110.4	+26.6%	+23.1%
Manure management (CH_4)	12.6	9.9	12.3	+18.8%	-0.5%
Rice cultivation (CH_4)	21.3	24.7	25.4	-11.3%	-15.7%
Agricultural CH_4 total	166.9	136.4	148.0	+19.0%	+13.7%



Source category (gas)	LandSyMM 2020	FAOSTAT 2020	EDGAR 2020	PBIAS vs FAOSTAT	PBIAS vs EDGAR
Manure management (N ₂ O) ^a	0.63	0.45	0.32	+29.0%	+86.7%
Managed soils (N ₂ O)	6.12	7.00	5.98	-8.3%	+3.4%
Agricultural N₂O total	6.76	7.44	6.30	-5.5%	+8.4%

^a2006 IPCC Guidelines emission factors (historical-evaluation basis; see text). 2020 totals are in Tg CH₄ yr⁻¹ (CH₄ rows) or Tg N₂O yr⁻¹ (N₂O rows); the aggregate CH₄ and N₂O totals are computed from the unrounded category values, so the rounded entries shown need not sum to them exactly (the agricultural N₂O total combines managed soils on the 2019 Refinement basis with manure management on the 2006 Guidelines basis, as in the component rows). Per-category species and regional decompositions, ratio-to-FAOSTAT diagnostics, and the synthetic-fertiliser N₂O sub-component are shown in the Supplement (Fig. S20).





770 **Figure 2.** Global historical agricultural-emission totals (1970-2020) for the five bottom-up Tier-1 source categories, each compared against the FAOSTAT and EDGAR 2025 inventories and the RCMIP (CMIP6) reference: (a) enteric-fermentation CH_4 , (b) manure-management CH_4 , (c) rice-cultivation CH_4 , (d) manure-management N_2O , and (e) managed-soils N_2O . The LandSyMM line is the IPCC Tier-1 estimate (Sect. 2.2); the RCMIP-derived series is the RCMIP CH_4 or N_2O global total apportioned to each category by its EDGAR sector share (the shaded fill marks the LandSyMM-to-FAOSTAT difference).
 775 Manure-management N_2O (d) is shown on the 2006 IPCC Guidelines basis, and managed soils (e) on the 2019 Refinement (with pasture/range/paddock) basis, consistent with Sect. 3.1. The per-category species and regional decompositions, the ratio-to-FAOSTAT diagnostics, and the synthetic-fertiliser N_2O sub-component of managed soils are provided in the Supplement (Fig. S20). Aggregate PBIAS and 2020 totals are reported in Table 9.

3.2 Integrated emissions and concentration trajectories (1900-2100)

780 3.2.1 Integrated emission trajectories across the five SSP-RCP scenarios

The integrated emissions (i.e., combining the bottom-up agricultural Tier-1 inventory, the LPJ-GUESS land-biosphere fluxes, and the residual RCMIP background (Sect. 2.4.4)), reproduce the observationally constrained global budgets closely at 2020 (Fig. 3): the integrated CH_4 total of 577 Tg yr^{-1} is within -5.1% of the Global Methane Budget (608 Tg , Saunio et al., 2025), the N_2O total of 26.1 Tg yr^{-1} within -2.2% of the Global Nitrous Oxide Budget (26.7 Tg , Tian et al., 2024), and the CO_2
 785 total within +4.3% of the Global Carbon Budget (Friedlingstein et al., 2025). The close agreement of the *total atmospheric source* (anthropogenic plus natural) with the observationally constrained budgets confirms that the bottom-up substitution and the LPJ-GUESS natural fluxes integrate to a present-day baseline consistent with the community budgets.

Across the five SSP-RCP scenarios the trajectories diverge from 2015 and span a wide range by 2100: CH_4 from 384 Tg yr^{-1} (SSP1-2.6) to 1157 Tg yr^{-1} (SSP3-7.0), N_2O from 21 to 42 Tg yr^{-1} , and the net CO_2 source from $-8.7 \text{ Gt CO}_2 \text{ yr}^{-1}$ (a
 790 net sink under SSP1-2.6) to $+99 \text{ Gt CO}_2 \text{ yr}^{-1}$ (SSP5-8.5) (Table 10). Relative to the observation-anchored reference (Fig. 3; the primary reference), the integrated CH_4 is higher at 2100 by +14% (SSP4-6.0) to +71% (SSP2-4.5), reflecting the bottom-up land-system CH_4 that the reference does not resolve. For CH_4 and N_2O the scenario-baseline reference (Fig. S21) gives the same scenario-period divergence, since the two references coincide outside the 1980-2020 window. For CO_2 they differ over the scenario period because the observation-anchored reference carries a land-sink (SLAND) correction. Against this, the net
 795 CO_2 source difference is small and changes sign across scenarios (from $+2.3 \text{ Pg C yr}^{-1}$ under SSP1-2.6 to $-2.2 \text{ Pg C yr}^{-1}$ under SSP5-8.5), whereas against the scenario-baseline reference, which has no explicit land sink, the integrated source is lower by $0.9\text{-}5.4 \text{ Pg C yr}^{-1}$ ($3.3\text{-}19.7 \text{ Gt CO}_2 \text{ yr}^{-1}$) across all scenarios, from explicitly capturing the LPJ-GUESS land sink in the integrated total.

Table 10. Integrated global emissions at 2020 (mean across scenarios) versus the observational budgets, and the 2100 spread
 800 across the five SSP-RCP scenarios.



Gas	Integrated 2020	Budget best (source)	Agreement (2020)	2100 range (min-max across SSPs)
CH ₄	577 Tg yr ⁻¹	608 Tg (GMB, Saunois et al., 2025)	-5.1%	384 (SSP1-2.6) – 1157 (SSP3-7.0) Tg yr ⁻¹
N ₂ O	26.1 Tg yr ⁻¹	26.7 Tg (GNB, Tian et al., 2024)	-2.2%	21 (SSP1-2.6) – 42 (SSP3-7.0) Tg yr ⁻¹
CO ₂	29.1 Gt CO ₂ yr ⁻¹	27.9 Gt CO ₂ (GCB, Friedlingstein et al., 2025)	+4.3%	-8.7 (SSP1-2.6) – +99 (SSP5-8.5) Gt CO ₂ yr ⁻¹

Agreement percentages are computed from the unrounded integrated and budget values, so they need not reproduce exactly from the rounded entries shown.

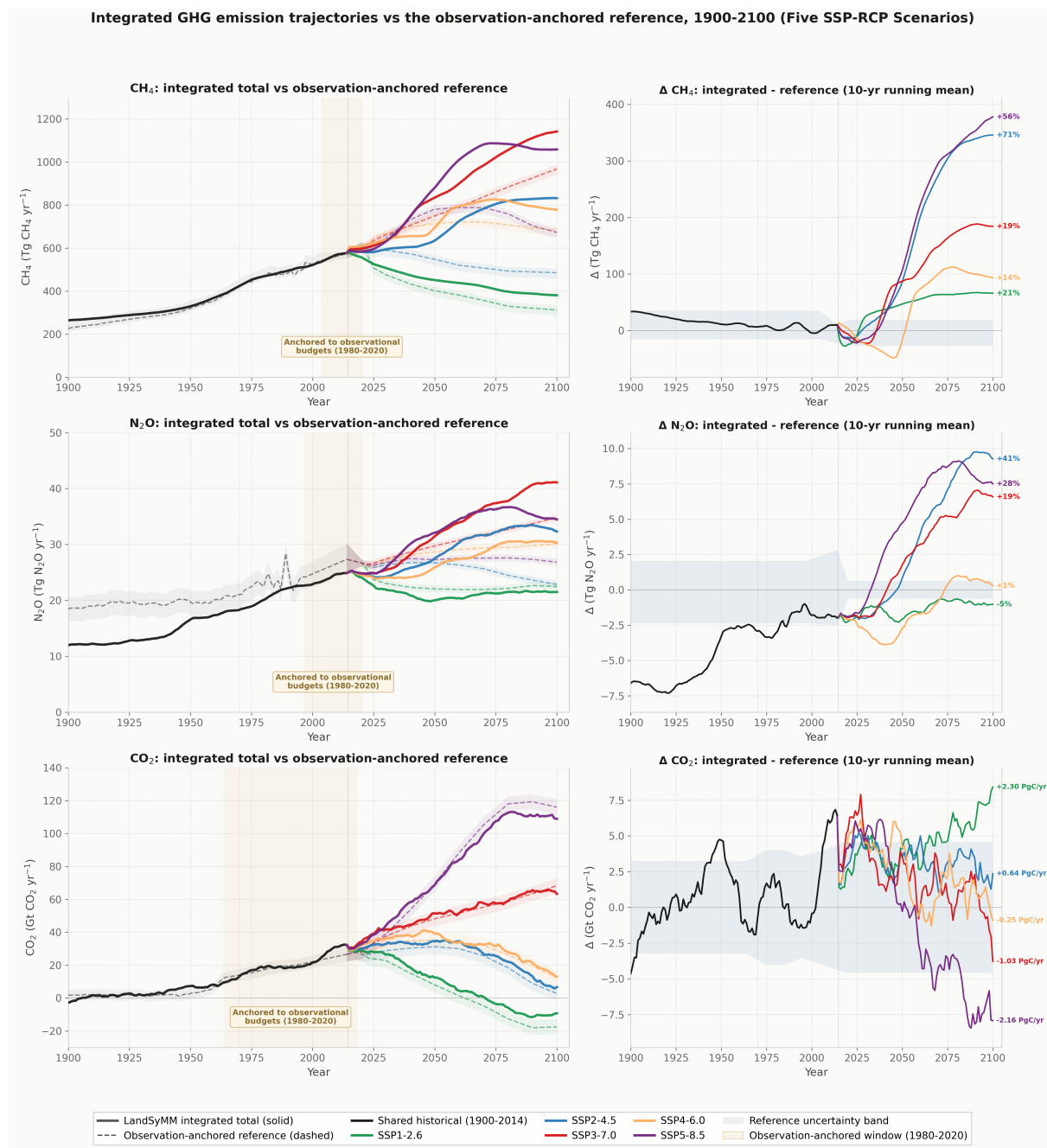


Figure 3. Integrated global GHG emission trajectories (anthropogenic + natural), 1900-2100, for the five SSP-RCP scenarios, compared against the observation-anchored reference (the primary reference of Sect. 2.3.4); one gas per row (CH₄, N₂O, CO₂). **Left panels:** the integrated LandSyMM total is drawn as a solid line (coloured by scenario from 2015, with the shared historical period in black to 2014) and the observation-anchored reference as a dashed line of the same colour, with its uncertainty band shaded. The shaded band is the reference's uncertainty envelope: over the 1980-2020 window it is the spread of the



observationally constrained global budgets, and outside that window it is carried from the RCMIP+FaIR reference, so it spans
 810 the full period (including the scenario projections) and is proportionally wider for N₂O, whose budget and natural-source un-
 certainty are larger. The reference follows the RCMIP+FaIR trajectory except over the shaded 1980-2020 window, where it is
 anchored to the observationally constrained global budgets (Global Methane, Nitrous Oxide and Carbon Budgets; Saunio et al.
 (2025); Tian et al. (2024); Friedlingstein et al. (2025)) through top-down inversions; for CO₂ a land-sink (SLAND) correction
 renders the reference as an atmospheric source consistent with the model's $E_{\text{FOS}} + F_{\text{net}}$ construction, applied throughout so
 815 the CO₂ reference does not rejoin the scenario-baseline reference outside the anchored window (cf. Fig. S21). **Right panels:**
 the difference (integrated minus reference, 10-year running mean) by scenario, with 2100 values annotated (per cent of the
 reference for CH₄ and N₂O; Pg C yr⁻¹ for CO₂). The CO₂ trajectory axis (left) is in Gt CO₂ yr⁻¹, while its difference (right)
 is annotated in Pg C yr⁻¹. Integrated anthropogenic emissions are the RCMIP-substituted totals (CH₄, N₂O) or the RCMIP
 fossil-and-industrial term (CO₂); natural fluxes are from LPJ-GUESS (wetland CH₄, completed with inland-freshwater and
 820 reservoir/canal sources from the Global Methane Budget; soil + fire N₂O; net land-atmosphere flux for CO₂). Vertical dotted
 lines mark the 1970 Tier-1 inventory start and the 2014/2015 historical-scenario divergence. The scenario-baseline reference
 (Option A; RCMIP+FaIR throughout, with the observational budgets overlaid) and the full anthropogenic/natural source de-
 composition are shown in the Supplement (Fig. S21).

3.2.2 Atmospheric concentration trajectories from IMOGEN/FaIR

825 The integrated emissions are converted to prognostic atmospheric concentrations by the IMOGEN FaIR module within the
 C++ engine. We assess the resulting CO₂, CH₄, and N₂O trajectories as a single continuous historical-to-scenario series (Fig.
 4): the shared historical concentration to 2015 is benchmarked against the observational record, after which the five SSP-RCP
 scenarios diverge to 2100. Because no observational counterpart exists for the future, the quantitative comparison (RMSD,
 mean bias) is computed over the historical period of overlap with the observed series (122 years, ~1900-2021); the scenario
 830 projections have no observational counterpart and are therefore shown to illustrate the projected trajectories rather than scored
 against observations. Evaluation statistics, computed per scenario over the overlap, are effectively identical across scenarios
 (the historical segment is shared) and are summarised as the across-scenario mean in Table 11.

The CO₂ trajectory reproduces the observed record closely, with an RMSD of 7.2 ppm and a small mean bias (+1.0 ppm)
 over the overlap, within the ≤ 10 ppm benchmark (Sect. 2.4.6). The small *mean* bias coexists with a +16 ppm offset at the
 835 2020 endpoint because the modelled trajectory runs marginally low through the early twentieth century and increasingly high
 through recent decades; the RMSD captures this spread rather than a systematic offset. The scenario fan spans 441 ppm
 (SSP1-2.6) to 1118 ppm (SSP5-8.5) at 2100, consistent with the CMIP6 SSP concentration range (Meinshausen et al., 2020).
 Methane is reproduced with an RMSD of 49.5 ppb and a low bias (-19.2 ppb), comfortably within the ≤ 100 ppb benchmark,
 the model tracking slightly beneath the post-2000 observed plateau; the 2100 fan ranges from 1337 ppb (SSP1-2.6) to 3836
 840 ppb (SSP3-7.0).

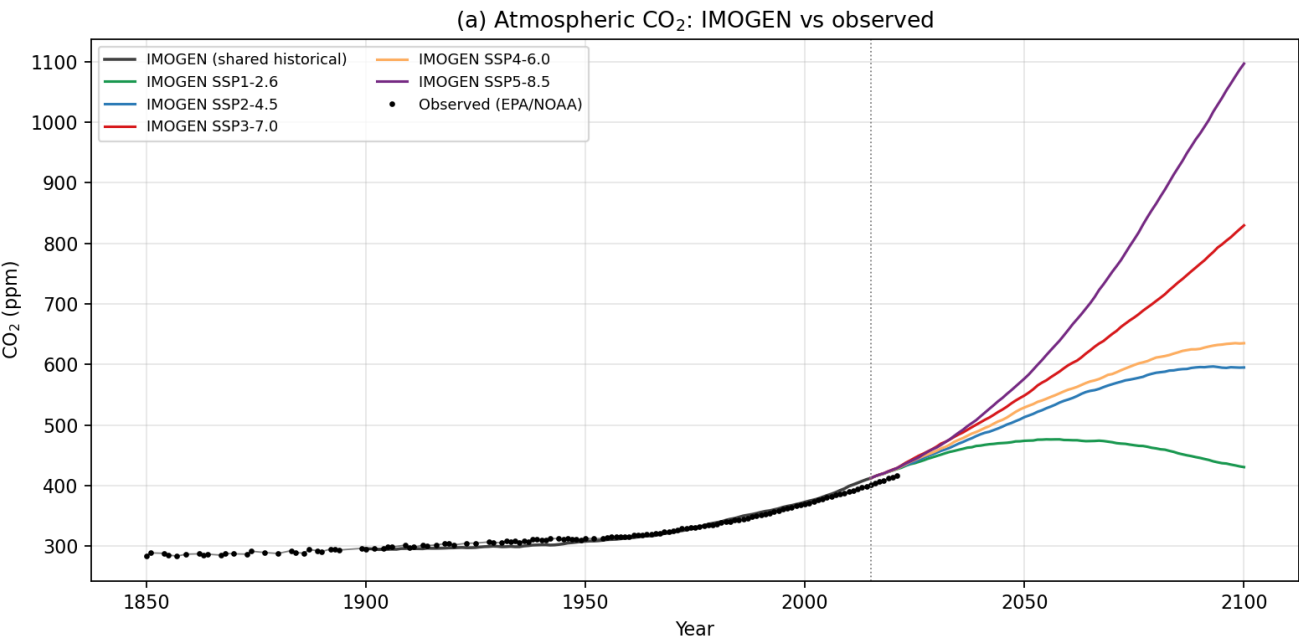
The nitrous-oxide trajectory likewise reproduces the observed record within its benchmark, with an RMSD of 5.6 ppb and
 a small mean low bias of -4.0 ppb over the overlap, inside the ≤ 15 ppb bound (Sect. 2.4.6). The modelled historical N₂O

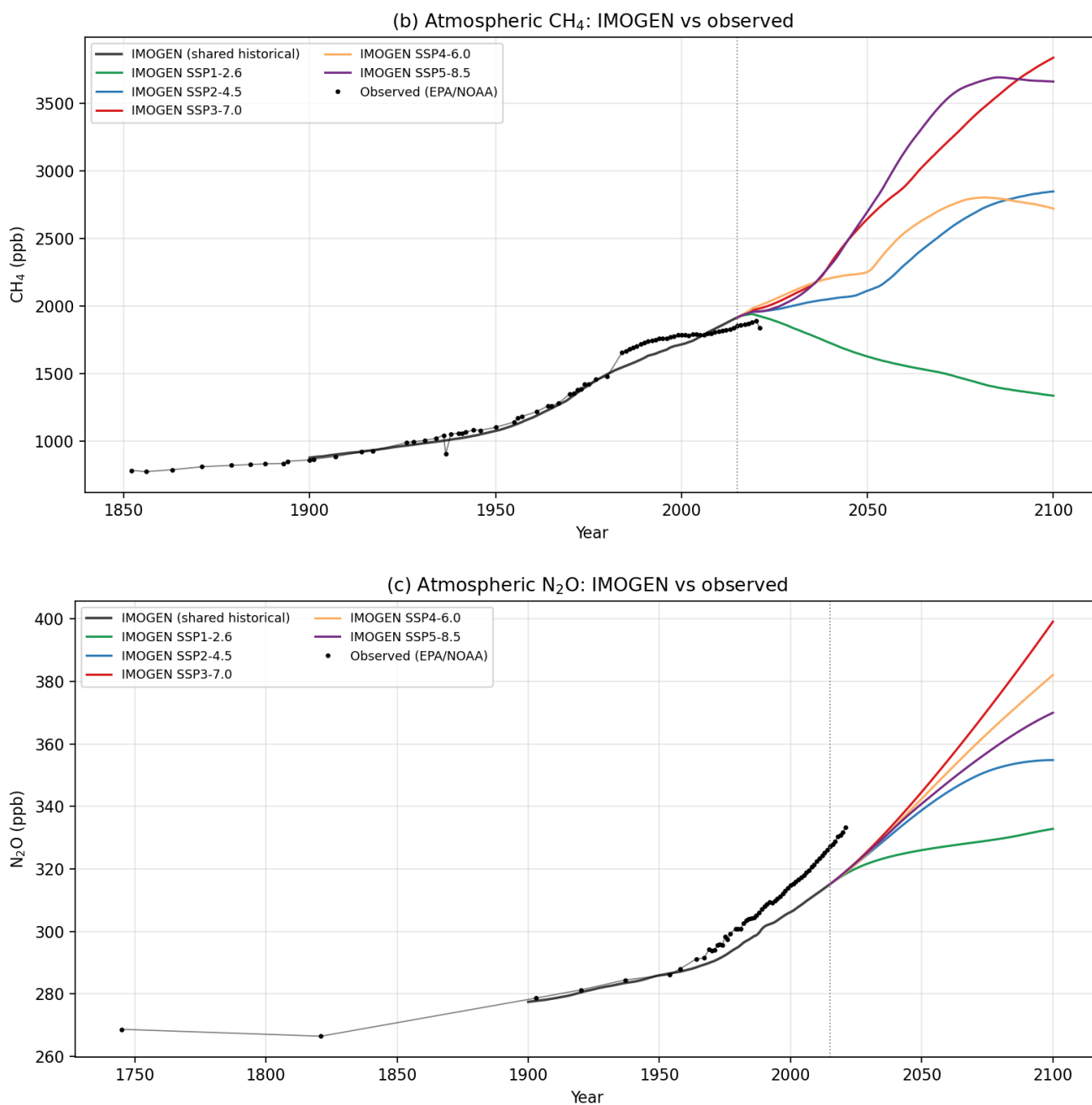


845 rises with the observed record from a near-correct early-century value (≈ 277 ppb at 1900), without an early-century decline, reaching 318 ppb at 2020 against an observed 332 ppb (a -14 ppb endpoint offset, comparable in relative terms to the modest CH_4 low bias). This is the N_2O trajectory consistent with the prescribed CMIP6 non- CO_2 radiative forcing that drives the coupled climate. It is produced when the integrated emissions carry the complete natural N_2O source – the LPJ-GUESS land-biosphere flux (soil plus fire) together with a prescribed ocean and non-land natural baseline (the FaIR natural-emissions term for ocean and other non-land N_2O ; Sect. 2.4.4). This ensures that the single-box budget is supplied with the full 14-17 Tg N_2O yr^{-1} natural source (consistent with Tian et al., 2024) rather than the land flux alone. The 2100 scenario fan spans 333
850 ppb (SSP1-2.6) to 399 ppb (SSP3-7.0), with the inter-scenario ordering following the SSP N_2O narratives (SSP3-7.0 highest, reflecting weak agricultural and air-pollution controls). The reproduction of all three gases within their benchmarks confirms that the bottom-up substitution drives IMOGEN to concentrations consistent with the community records for the species that dominate the integrated radiative forcing.

Table 11. Evaluation statistics for the IMOGEN/FaIR atmospheric concentration trajectories against the observational record
855 over the historical overlap (~ 1900 -2021; across-scenario mean, $n = 122$ yr). RMSD and mean bias are in native concentration units; the benchmark is the relaxed, uncertainty-scaled bound of Sect. 2.4.6.

Gas	RMSD	Mean bias	Benchmark	Verdict
CO_2	7.2 ppm	+1.0 ppm	≤ 10 ppm	Pass
CH_4	49.5 ppb	-19.2 ppb	≤ 100 ppb	Pass
N_2O	5.6 ppb	-4.0 ppb	≤ 15 ppb	Pass





860 **Figure 4.** Prognostic atmospheric concentration trajectories from the IMOGEN/FaIR module, 1850/1900-2100, for (a) CO₂,
 (b) CH₄, and (c) N₂O. The shared historical concentration (dark grey) diverges at 2015 (dotted line) into the five SSP-RCP
 scenarios; the observational reference (black; EPA/NOAA-GML/AGAGE instrumental record extended with the Law Dome
 ice core) is overlaid over its period of coverage. Evaluation statistics (Table 11) are computed over the historical overlap only;



the scenario fan is prognostic and is not scored against a reference. In panel (c) the modelled N₂O tracks the observed rise within the ≤ 15 ppb benchmark (RMSD 5.6 ppb), reflecting the budget being supplied with the complete natural N₂O source (land-biosphere plus ocean/non-land baseline) consistent with the prescribed CMIP6 forcing.

3.3 Climate forcing differences (IMOGEN-coupled vs ISIMIP-3b prescribed climate)

3.3.1 Temperature, precipitation, and shortwave radiation

Because the IMOGEN pattern-scaling and the ISIMIP-3b reference derive from the *same* GCM (MRI-ESM2-0; Sect. 2.4), the differences reported below isolate the combined effect of the pattern-scaling emulation and the coupled framework's own integrated forcing, and are not attributable to a mismatch in GCM identity.

The emulated climate reproduces the reference in both spatial pattern and global-mean magnitude. The spatial pattern correlation is $r \approx 0.98$ for temperature, ≈ 0.94 for shortwave radiation, ≈ 0.89 for precipitation, and ≈ 0.87 for the diurnal temperature range (Fig. 5; Table 12), and the global-mean near-surface temperature agrees with the reference to within about 0.3 K across all five scenarios and all analysis windows: the temperature difference (IMOGEN-coupled minus ISIMIP-3b) ranges from -0.03 to +0.15 K over 2015-2020, from -0.32 to -0.22 K over 2040-2060, and from -0.13 to +0.17 K by 2080-2100 (Table 12), with no systematic dependence on forcing. A residual mean-state difference between the observation-based baseline climatology to which the pattern-scaled anomalies are referenced (CRU-JRA; Sect. 2.4) and the ISIMIP-3b reference mean state persists at the regional scale. However, it is near-neutral in the global mean and does not project onto the global-mean difference. Precipitation carries a small dry bias (about -0.14 to -0.25 mm day⁻¹) that is nearly invariant across scenarios and windows, with the precipitation field varying with scenario (normalised spatial standard deviation ≈ 0.80 -0.89); shortwave radiation is mildly bright at the baseline window (+2.7 to +3.4 W m⁻²) and ranges from -2.3 to +1.6 W m⁻² by end of century across the five scenarios (Table S1). The identical-emulator diagnostic (Sect. 2.4.6) shows the emission-pathway feedback on global-land-mean temperature to be a cooling of 0.2 to 0.5 K relative to the unmodified-RCMIP climate (because the explicit LPJ-GUESS land sink lowers the integrated net CO₂), independent of the baseline choice (Fig. S19, Table S6). The high spatial-pattern fidelity ($r \approx 0.98$ for temperature) together with the near-zero global-mean difference means the climate driving the ecosystem simulation reproduces the reference in both geographic structure and global-mean magnitude, with the residual regional mean-state difference the principal signal carried into the ecosystem comparison (Sect. 3.4).



Taylor diagrams: IMOGEN-coupled vs ISIMIP-3b MRI-ESM2-0 (spatial pattern fidelity)

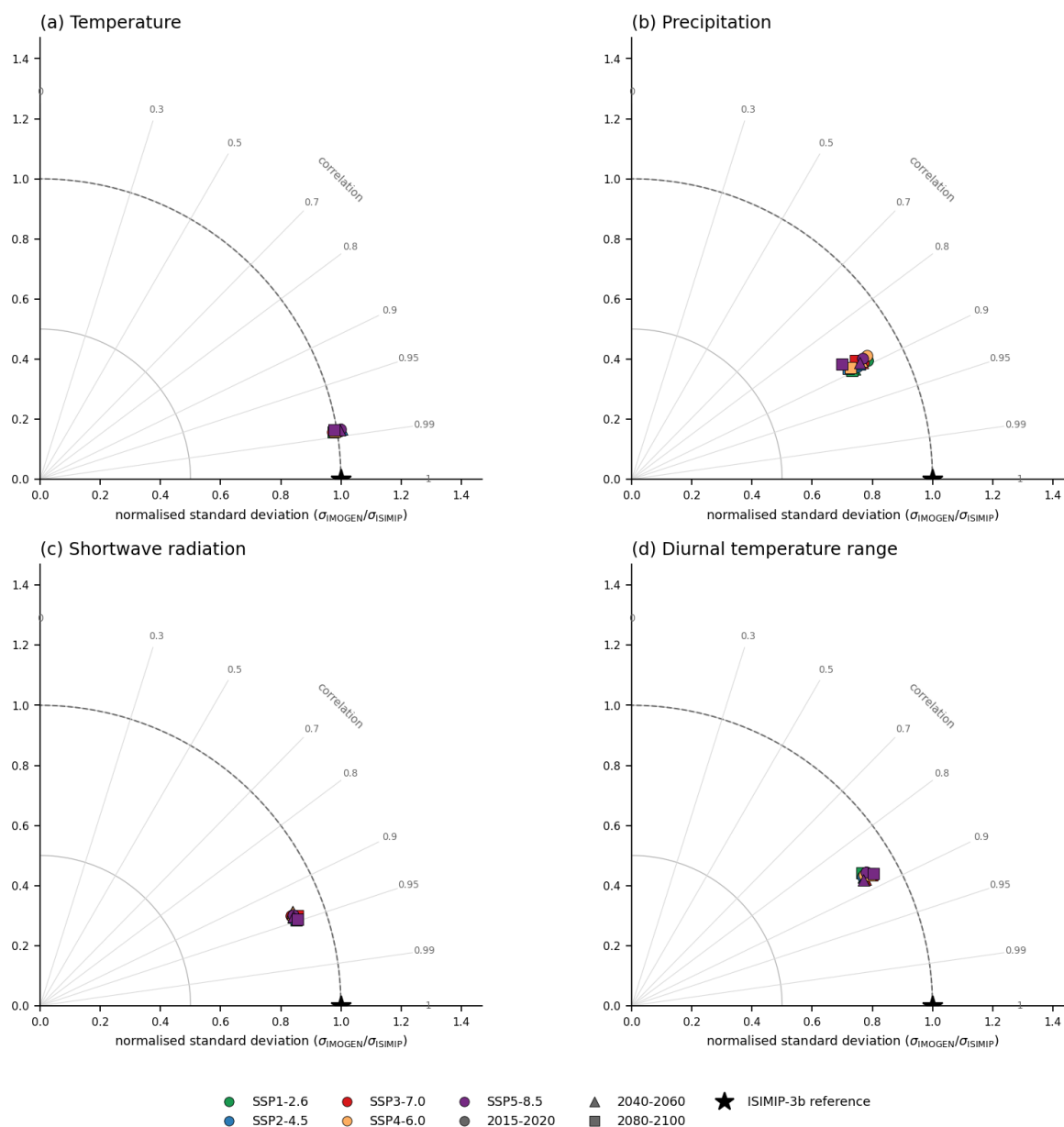


Figure 5. Taylor diagrams of the IMOGEN-coupled climate against the ISIMIP-3b MRI-ESM2-0 reference, for four fields – (a) near-surface air temperature, (b) precipitation, (c) downwelling shortwave radiation, and (d) diurnal temperature range – with the five SSP-RCP scenarios (colour) and three analysis windows (marker) shown in each panel against the reference (star). The points cluster close to the reference across all variables, scenarios, and windows: the spatial pattern correlation is $r \approx 0.98$ for temperature, ≈ 0.94 for shortwave radiation, ≈ 0.89 for precipitation, and ≈ 0.87 for the diurnal temperature



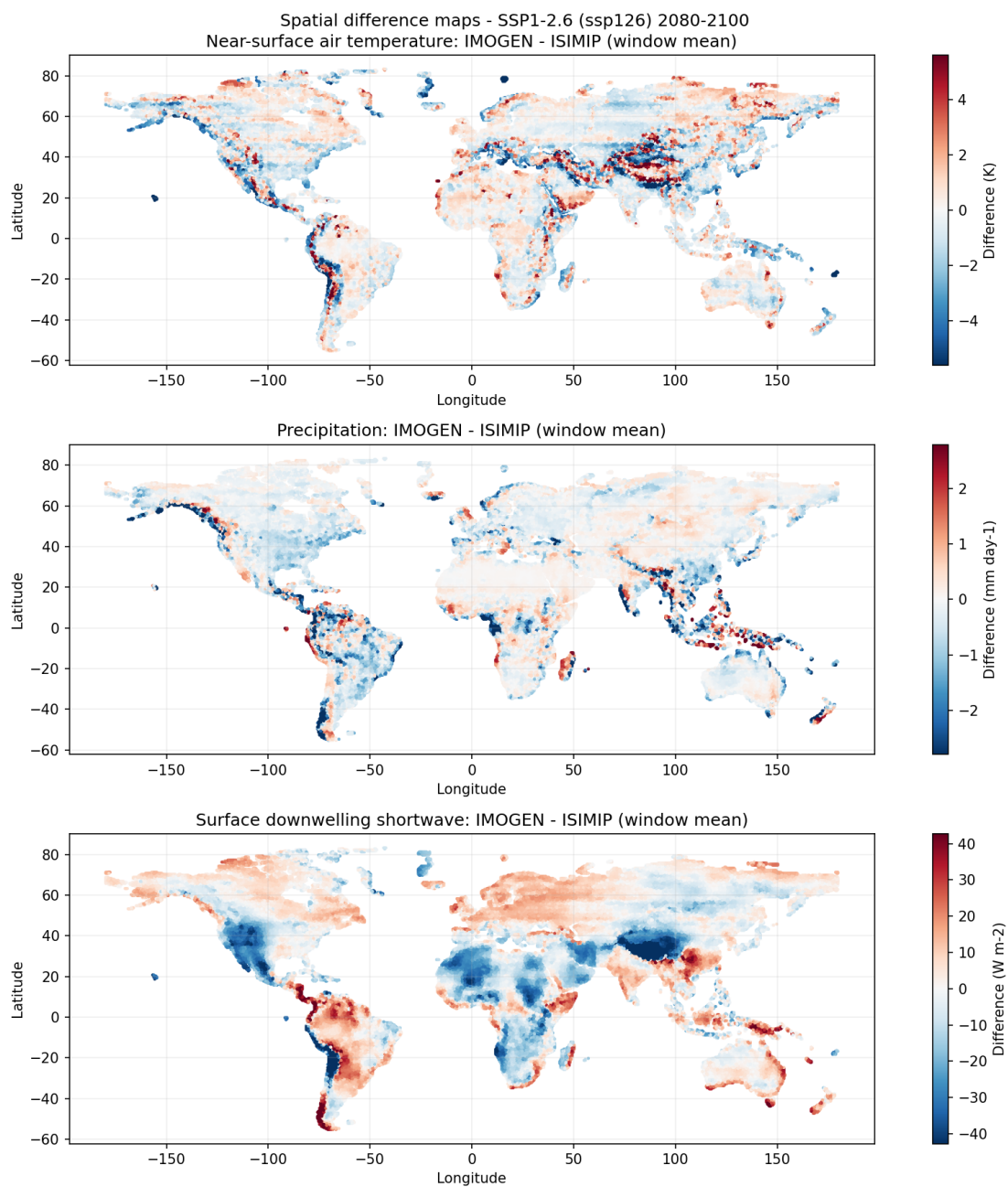
895 range, with the normalised spatial standard deviation within roughly 0.8-1.0 of the reference – i.e. the emulator reproduces the spatial structure of all four fields well. All statistics are cosine-latitude (gridcell-area) weighted (Sect. 2.4.6).

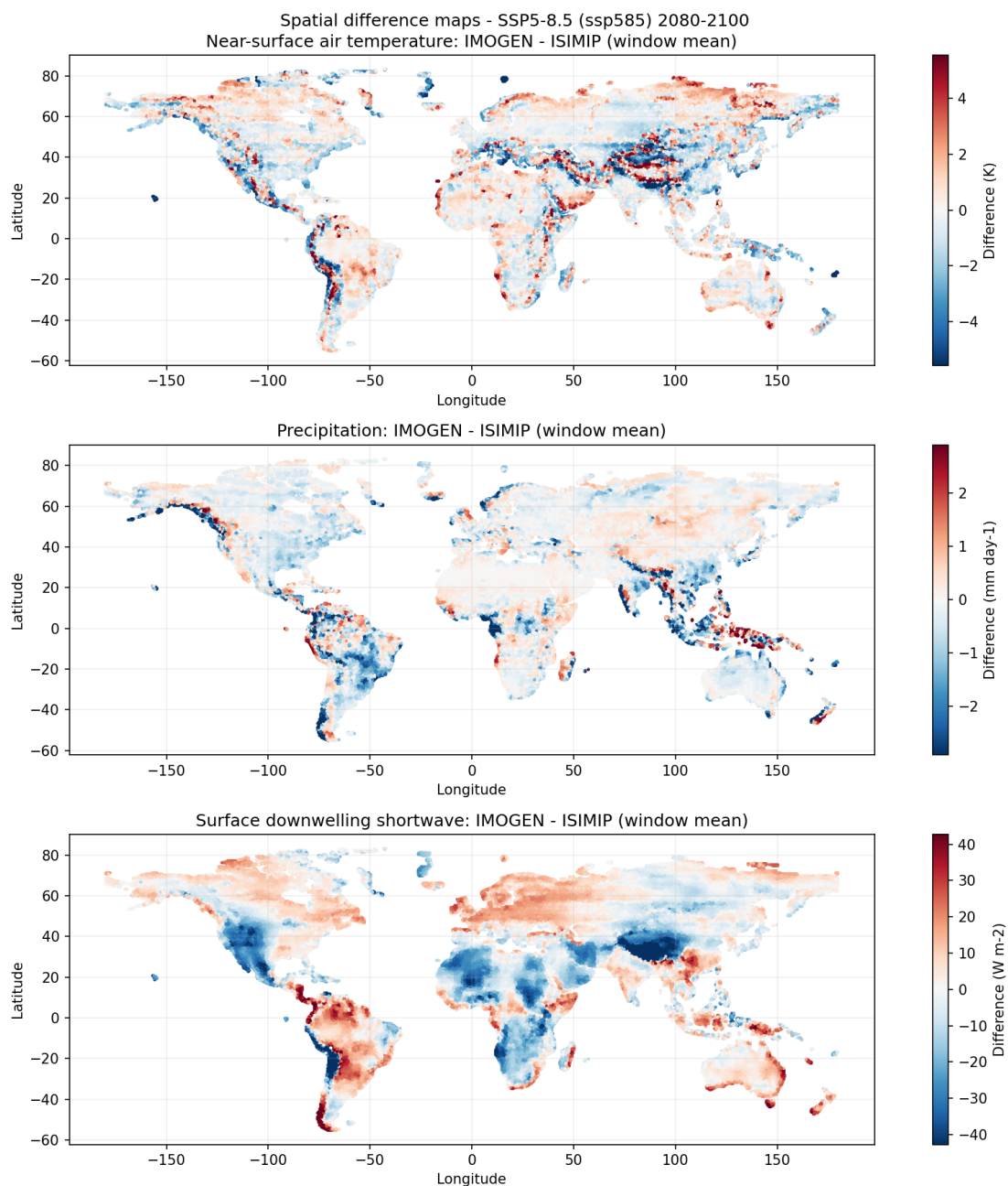
Table 12. IMOGEN-coupled vs ISIMIP-3b climate: global-mean bias (IMOGEN – ISIMIP) and spatial pattern correlation, by headline variable. Each bias column gives the range (the two most extreme values) across the five scenarios for that window; full per-scenario, per-window, and Supplement-variable statistics are in Table S1. All bias and pattern-correlation statistics are cosine-latitude (gridcell-area) weighted (Sect. 2.4.6). The tabulated spatial r is a representative across-scenario value; per-scenario, per-window correlations (for temperature, 0.986-0.987) are given in Table S1. Full-period (1900-2100) global-land-mean trajectories of the three headline variables, for both configurations and all five scenarios, are shown in the Supplement (Figs S28-S30, Sect. S9).

Variable	Bias, 2015-2020	Bias, 2080-2100	Spatial r
Temperature (K)	-0.03 to +0.15	-0.13 to +0.17	0.98
Precipitation (mm day ⁻¹)	-0.19 to -0.14	-0.25 to -0.19	0.89
Shortwave (W m ⁻²)	+2.7 to +3.4	-2.3 to +1.6	0.94

3.3.2 Spatial difference maps

905 The spatial structure of the difference is mapped for the end-of-century (2080-2100) window for the two bracketing scenarios (Fig. 6), with the three intermediate scenarios and a mid-century (2040-2060) example provided in the Supplement (Figs. S3, S4). The temperature difference is small and regionally mixed, near-neutral in the global mean, and does not intensify systematically with forcing or time. It reflects the residual regional mean-state difference between the observation-based baseline climatology and the ISIMIP-3b reference mean state (Sect. 3.3.1) as opposed to a coherent warm or cool difference, while the spatial *pattern* of the field itself remains closely matched ($r \approx 0.98$). The largest regional differences follow the topographic and land-surface contrasts between the two mean-state climatologies. The precipitation difference is comparatively small and regionally mixed, and the shortwave difference is modest and of mixed sign across regions and scenarios.





915 **Figure 6.** Spatial difference (IMOGEN-coupled minus ISIMIP-3b MRI-ESM2-0) in the headline climate variables (near-surface air temperature, precipitation, downwelling shortwave radiation) for the end-of-century window (2080-2100), for the two bracketing scenarios: (a) SSP1-2.6 (low forcing) and (b) SSP5-8.5 (high forcing). The temperature difference is small and regionally mixed in both scenarios, near-neutral in the global mean and without a systematic forcing dependence, while the



spatial pattern of each field remains closely matched ($r \approx 0.98$ for temperature). End-of-century maps for the three intermediate
 920 scenarios (Fig. S3) and a mid-century example (Fig. S4) are provided in the Supplement.

3.4 Ecosystem response differences (IMOGEN-coupled vs ISIMIP-3b prescribed climate)

The ecosystem-state consequences of the coupled feedback climate are assessed by comparing the LPJ-GUESS output of
 the IMOGEN-coupled configuration against that of the ISIMIP-3b prescribed-climate configuration over the end-of-century
 window (2080-2100), for all five SSP-RCP scenarios. The two configurations are identical except for the climate forcing and
 925 its associated atmospheric CO₂ trajectory – the IMOGEN-coupled climate versus the ISIMIP-3b MRI-ESM2-0 prescribed
 reference (Sect. 2.4). The comparison is therefore a controlled experiment in which the climate-and-CO₂ driver is the single
 differential. Because both configurations are built on the same MRI-ESM2-0 basis (Sect. 3.3.1) and the coupled run is driven
 by the framework’s own integrated emissions, which diverge from the RCMIP trajectory that underlies the prescribed reference
 (Sect. 3.2.1; Fig. 3), the differences reported here contain a genuine coupled-model emission-pathway feedback. The identical-
 930 emulator diagnostic isolates this feedback at the climate level (Sect. 2.4.6, 4.4), demonstrating that the framework can attribute
 the emission-pathway signal even against the community-standard ISIMIP-3b prescribed reference and despite the difference
 in baseline climatology between the two; the corresponding ecosystem-level differences reported below are superimposed on,
 and largely accounted for by, a persistent baseline-climatology offset between the two configurations’ mean states (Sect. 3.4.1).
 The two bracketing scenarios (SSP1-2.6 and SSP5-8.5) are presented in the main text and the three intermediate scenarios in
 935 the Supplement (Sect. S3); all differences are reported as IMOGEN-coupled – ISIMIP-3b, area-weighted over land.

3.4.1 Carbon pools and fluxes, productivity, and crop yields

Because the two configurations spin up under different baseline climatologies – the emulator’s CRU-JRA baseline versus the
 W5E5-anchored ISIMIP-3b reference (Sect. 3.3.1) – LPJ-GUESS equilibrates to different initial carbon pools, so a persistent,
 roughly forcing-independent offset of about +624 Pg C in total ecosystem carbon (equivalently about +4.3 kg C m⁻²) is
 940 present from the start of the simulation. The total-carbon offset at 1901 (+624 Pg C) and the initial offsets for all ecosystem-
 state variables (at the present-day reference) are tabulated in the Supplement (Sect. S3, Table S3). Because the absolute pools
 differ by construction, the meaningful comparison is between the *changes* from a present-day reference (2005-2025) to the
 end of century (2080-2100), and these track each other closely between the two configurations (Table 13). Under SSP5-8.5,
 total ecosystem carbon increases by +205 Pg C in the coupled configuration and by +231 Pg C in the prescribed configuration,
 945 a difference of -26 Pg C, and an order of magnitude smaller than the +624 Pg C baseline offset. The same, near-parallel
 behaviour holds across all five scenarios (Table 13; Figs. 9, 10). This close tracking of the changes is a consistency check:
 the emulated-climate ecosystem trajectory reproduces the reference-climate trajectory, and the emission-pathway feedback
 is isolated separately by the identical-emulator diagnostic (Sect. 2.4.6, 4.4). The baseline offset is distributed across the soil
 and litter pools – soil carbon higher by about +403 Pg C and litter carbon by about +125 Pg C, with a vegetation-carbon
 950 contribution of about +96 Pg C (these three pools summing to the +624 Pg C total at 1901; the total additionally includes
 a small harvested wood-product pool that is near zero at that time). The spatial pattern of the carbon field is closely aligned



between the two configurations (spatial pattern correlation $r \approx 0.85$ - 0.86 for total carbon; Table S2): the configurations agree on the geography of the carbon distribution, and their difference is expressed as a spatially coherent offset rather than as pattern disagreement. That offset is positive across most of the vegetated land surface – more than four-fifths of land gridcells (about 83%) – and is largest across the boreal and cool-temperate soil-carbon zones of northern Eurasia and North America (Fig. S31), and is smaller, and negative in places, across the warmer lower latitudes. That a near-neutral, high-fidelity climate difference (Sect. 3.3) produces a stock offset of this size reflects the higher baseline productivity of the coupled configuration combined with the long turnover time of soil carbon. The two observation-based baseline climatologies differ only modestly in the global-land annual mean – near-identical temperature, a slightly drier coupled climate (by about 0.15 to 0.20 mm day⁻¹ in the global-land annual mean; Fig. S29) and a modestly brighter baseline shortwave flux (Table 12). The coupled configuration is nonetheless persistently more productive (higher net primary production and leaf area index; see below), consistent with the brighter baseline shortwave flux more than offsetting the modest precipitation deficit, so a small but persistent surplus of carbon inputs enters the litter and soil pools. Because soil carbon turns over slowly, this input surplus accumulates over the multi-century spin-up, so that a modest per-area difference (about $+2.8$ kg C m⁻² in soil carbon) sums to a large global total even as the annual-mean climate difference remains near-neutral. The larger stores in turn sustain the slightly higher absolute heterotrophic respiration reported below at near-steady state.

The fluxes and the secondary ecosystem-state variables are likewise dominated by the persistent offset. The values quoted in the remainder of this section are the absolute coupled-minus-prescribed differences over the end-of-century window (Table S2), i.e. further components of that offset. The corresponding scenario-period *changes*, which are small and track between the two configurations, are given in Table 13 and Table S3. Ranges quoted below span the two bracketing scenarios (SSP1-2.6, SSP5-8.5) unless stated as across all five. The carbon fluxes are consistent with the stock offset: net primary production is higher in the coupled configuration by a small, nearly forcing-independent amount ($+0.060$ kg C m⁻² yr⁻¹ at SSP1-2.6 and $+0.065$ kg C m⁻² yr⁻¹ at SSP5-8.5; $r \approx 0.88$ - 0.89), arising in natural vegetation. Vegetation net carbon uptake and soil heterotrophic respiration are both larger in the coupled configuration (vegetation flux -0.060 to -0.065 kg C m⁻² yr⁻¹ more negative, i.e. greater uptake; soil respiration $+0.055$ to $+0.059$ kg C m⁻² yr⁻¹ larger), while the net land-atmosphere carbon flux (F_{net} , which also incorporates fire and land-management exchanges; Sect. 2.2.6) remains small ($+0.002$ to $+0.007$ kg C m⁻² yr⁻¹) with weak spatial correspondence ($r \approx 0.06$ - 0.23). The dominant carbon signal is thus in the stocks rather than in the near-balanced net flux, with the larger soil and litter reservoirs sustaining a slightly higher absolute respiration flux at near-steady state.

Crop-yield differences between the two configurations are small and mixed in sign. Rice and nitrogen-fixing oil crops are modestly higher in the coupled configuration (rice $+0.022$ to $+0.106$ kg C m⁻² yr⁻¹; N-fixing oil crops $+0.075$ to $+0.128$ kg C m⁻² yr⁻¹), the C4 cereals are slightly higher ($+0.002$ to $+0.034$ kg C m⁻² yr⁻¹), and the C3 cereals are marginally lower (-0.010 to -0.005 kg C m⁻² yr⁻¹), while the other-oil-crop difference is consistently slightly negative (-0.008 to -0.025 kg C m⁻² yr⁻¹) and pulses are consistently higher in the coupled configuration ($+0.045$ to $+0.135$ kg C m⁻² yr⁻¹); these ranges span the five scenarios (Table S2). The yield fields are spatially well aligned between the two configurations ($r \approx 0.70$ - 0.94 across the cereal and rice categories). These are small differences between two model configurations under identical land use



and management, arising from the regional mean-state climate and atmospheric CO₂ differences of Sect. 3.3-3.4 rather than from a systematic warming of the coupled climate, and are not a projection of absolute yield change.

The remaining ecosystem-state variables, reported in full in the Supplement (Sect. S3), track the larger carbon and nitrogen reservoirs of the coupled configuration. For the bracketing scenarios, soil N₂O emissions are modestly higher (+0.05 to +0.07 kg N ha⁻¹ yr⁻¹), consistent with the larger soil organic-matter and moisture reservoirs; across all five scenarios, however, the soil-N₂O and total soil N-gas differences are small and mixed in sign (Table S2), reflecting the low spatial coherence of the N₂O response ($r \leq 0.57$). Wetland CH₄ is higher (+0.16 to +0.18 g CH₄ m⁻² yr⁻¹); leaf area index is higher (+0.34 to +0.39 m² m⁻²); and the total ecosystem nitrogen pool is larger (+0.28 kg N m⁻²), tracking the enlarged soil organic-matter store. Total runoff is lower (by 134 to 150 mm yr⁻¹ across the scenarios) and nitrogen leaching is reduced (by 0.84 to 1.12 kg N ha⁻¹ yr⁻¹), consistent with the small precipitation dry difference (Sect. 3.3.1) together with the higher leaf area and evapotranspiration of the coupled configuration.

Table 13. Ecosystem-state *changes* from a present-day reference (2005-2025) to end of century (2080-2100), for the IMOGEN-coupled and ISIMIP-3b prescribed configurations, and the difference in the change (Δ_{chg} = coupled change – prescribed change), for the two bracketing scenarios. Comparing changes removes the persistent baseline-climatology offset between the two spin-ups (present from the start of the simulation; tabulated for all variables and scenarios in Table S3), so that the near-parallel trajectories of the two configurations (Figs. 9, 10) are compared on a common footing; Δ_{chg} is small relative to each change. Carbon pools and fluxes are reported as global totals (Pg C or Pg C yr⁻¹); crop yields, being per-crop intensities, are given as the change in the production-weighted area mean (kg C m⁻² yr⁻¹, weighted by harvested area). Total ecosystem carbon additionally includes a harvested slow-carbon (wood-product) pool beyond the vegetation, litter, and soil pools listed here (about +4 to +5 Pg C in stock, itself higher in the coupled configuration by about +0.7 Pg C, i.e. offset in the same direction as the other pools); this pool changes slightly over the century, so the three listed pools are not expected to sum exactly to the total change. Values are computed from unrounded fields and may not reproduce exactly from the rounded coupled and prescribed columns. The end-of-century absolute levels and differences are in Table S2, and the initial baseline offsets and difference-in-change for all variables and five scenarios in Table S3.

Variable	Unit	SSP1-2.6 coupled	prescribed	Δ_{chg}	SSP5-8.5 coupled	prescribed	Δ_{chg}
Total ecosystem carbon	Pg C	+122	+138	-17	+205	+231	-26
Soil carbon	Pg C	+2	+10	-8	-5	+11	-16
Litter carbon	Pg C	+32	+37	-5	+31	+46	-16
Vegetation carbon	Pg C	+91	+93	-3	+181	+175	+6



Variable	Unit	SSP1-2.6 coupled	prescribed	Δ_{chg}	SSP5-8.5 coupled	prescribed	Δ_{chg}
Net primary production	Pg C yr ⁻¹	+0.8	+2.8	-2.0	+21.4	+22.8	-1.4
Net land-atmosphere C flux (F_{net})	Pg C yr ⁻¹	+0.1	-0.1	+0.2	-3.1	-4.0	+0.9
C4 cereal yield	kg C m ⁻² yr ⁻¹	+0.013	+0.003	+0.010	+0.058	+0.016	+0.042
Rice yield	kg C m ⁻² yr ⁻¹	-0.004	-0.008	+0.003	+0.301	+0.215	+0.086
C3 cereal yield	kg C m ⁻² yr ⁻¹	-0.009	-0.013	+0.004	+0.077	+0.068	+0.009
N-fixing oil-crop yield	kg C m ⁻² yr ⁻¹	+0.019	+0.022	-0.002	+0.278	+0.235	+0.043

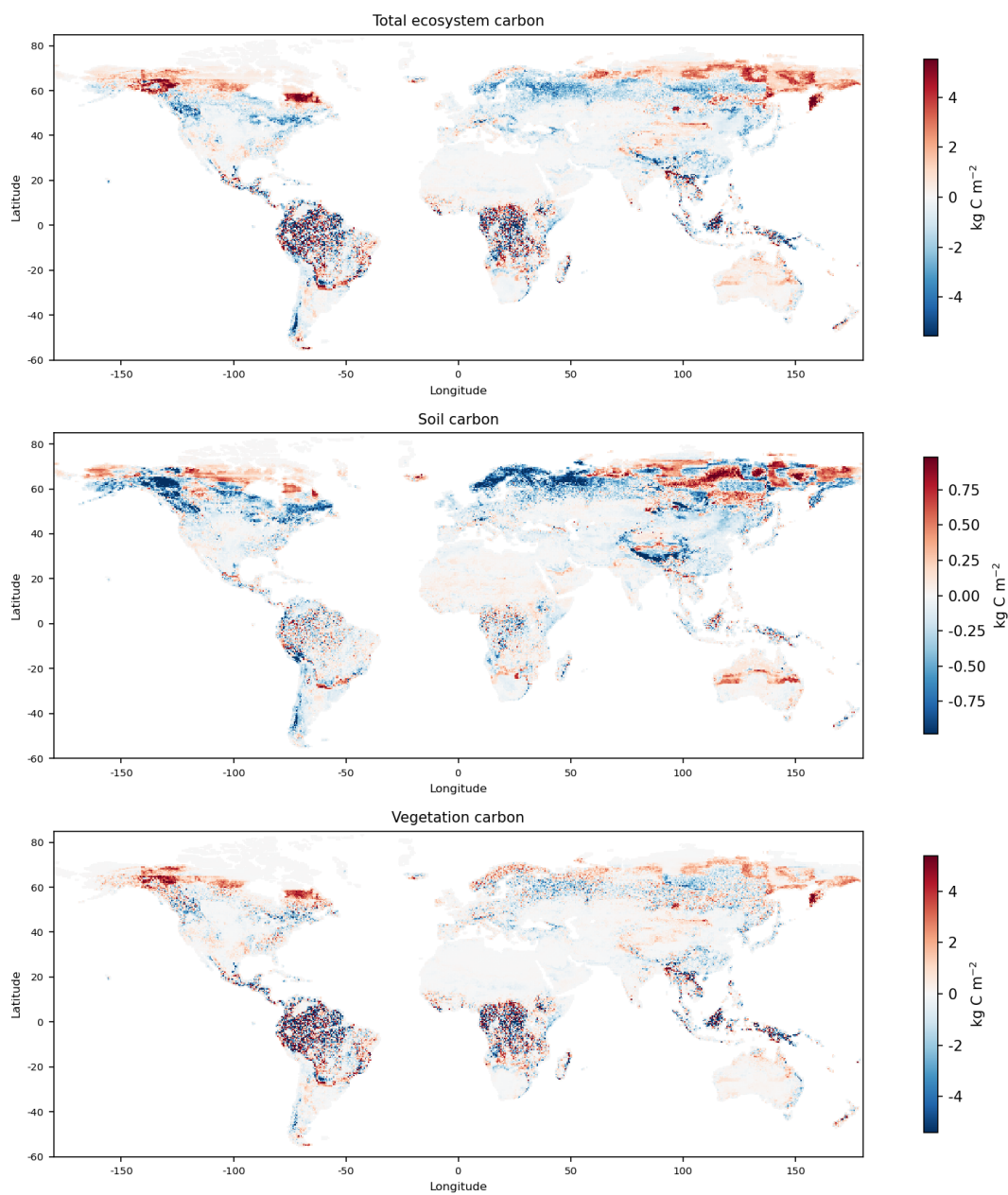
3.4.2 Spatial difference maps

The spatial structure of the carbon response is mapped for the two bracketing scenarios in Fig. 7 as the difference in the present-day-to-end-of-century change between the two configurations, which removes the persistent baseline-climatology offset (Sect. 3.4.1) and isolates where their responses differ. The difference in the total-ecosystem-carbon change is small in magnitude, with a weak band of opposing sign at high latitudes. Specifically, there is a modest negative difference across boreal Eurasia and central-northern North America, flanked by positive fringes at the highest latitudes, and salt-and-pepper patches across the cool-temperate and tropical zones, which largely offset in the global total (Table 13). The pattern is similar between SSP1-2.6 and SSP5-8.5, and the configurations' underlying carbon fields remain closely matched ($r \approx 0.85$ -0.86; Table S2), confirming near-parallel trajectories once the baseline offset is removed.

The difference in the crop-yield change (Fig. 8), formed in the same way by differencing the present-day-to-end-of-century change between the two configurations so as to remove the baseline offset, is small and regionally mixed in sign across all four crops, without a coherent large-scale pattern. Maps for the three intermediate scenarios are provided in the Supplement (Figs. S6, S7).

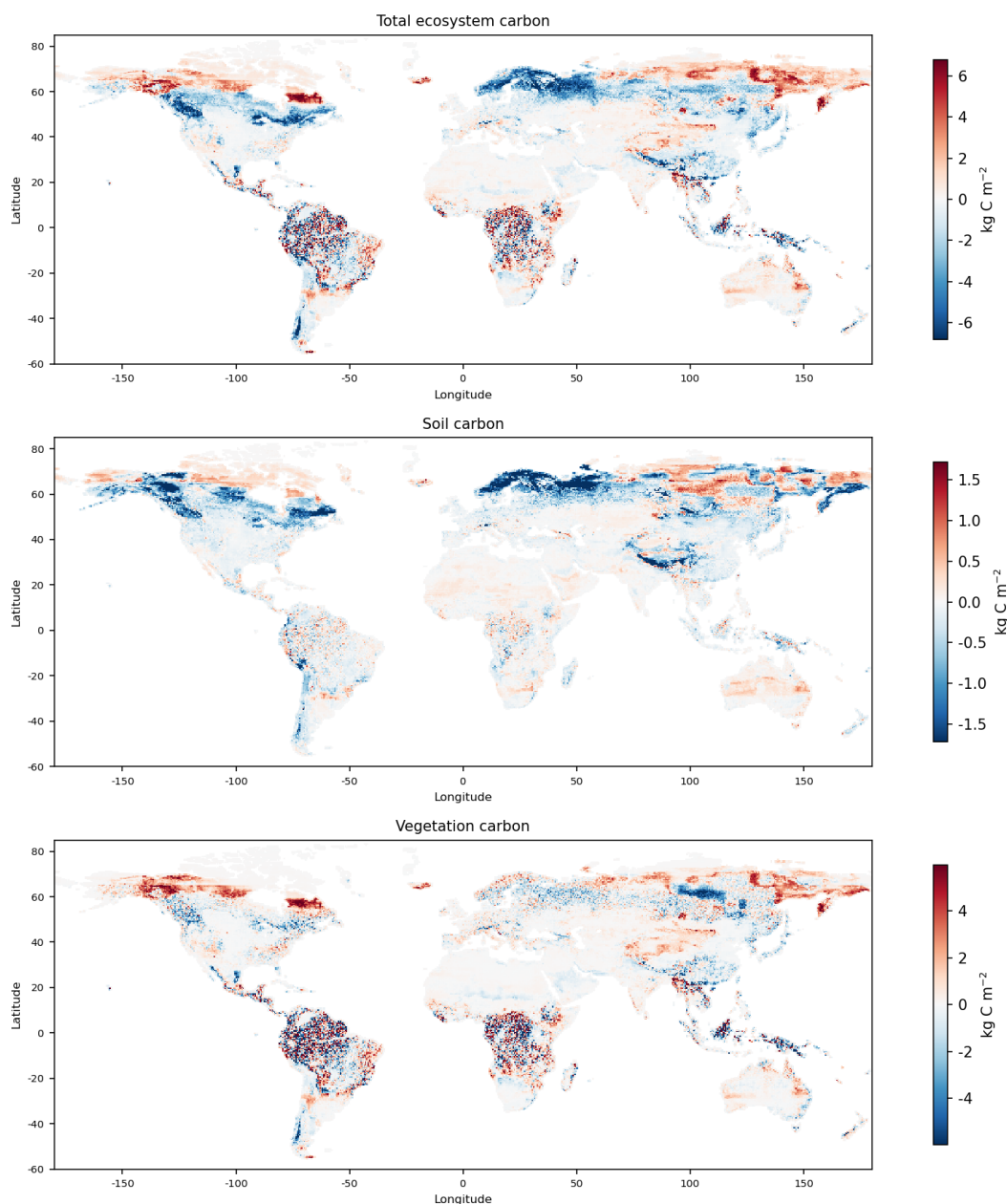


Difference in the present-day-to-end-of-century carbon change (IMOGEN-coupled - ISIMIP-3b), SSP1-2.6 (low forcing) (2005-2025 to 2080-2100)





Difference in the present-day-to-end-of-century carbon change (IMOGEN-coupled - ISIMIP-3b), SSP5-8.5 (high forcing) (2005-2025 to 2080-2100)



1025

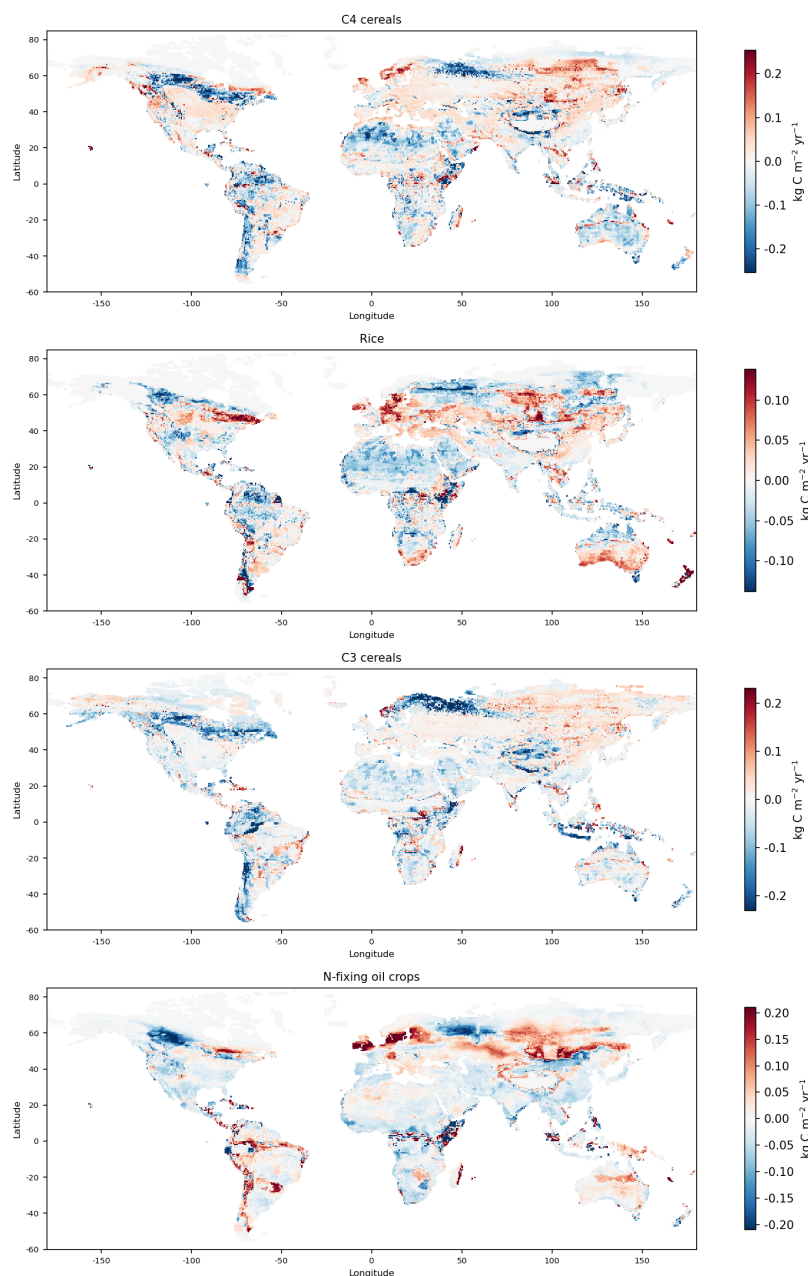
Figure 7. Difference in the present-day-to-end-of-century *change* in ecosystem carbon (IMOGEN-coupled minus ISIMIP-3b prescribed), for the two bracketing scenarios: (a) SSP1-2.6 and (b) SSP5-8.5. Each panel set shows total ecosystem carbon, soil carbon, and vegetation carbon, as the difference between the two configurations' change from the present-day reference (2005-2025) to the end of century (2080-2100). Differencing the change removes the time-invariant baseline-climatology offset (Sect. 3.4.1), so the maps show where the two configurations' carbon *responses* differ rather than the persistent offset. The differences

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are small in magnitude and dominated by a weak high-latitude band of opposing sign that largely offsets in the global total, consistent with the close tracking of the two configurations' changes (Table 13). Equivalent maps for the three intermediate scenarios are in the Supplement (Fig. S6); the corresponding absolute difference maps, which retain the baseline-climatology offset, are given for all five scenarios in the Supplement (Fig. S31).

ifference in the present-day-to-end-of-century crop-yield change (IMOGEN-coupled - ISIMIP-3b), SSP1-2.6 (low forcing) (2005-2025 to 2080-2100)





ifference in the present-day-to-end-of-century crop-yield change (IMOGEN-coupled - ISIMIP-3b), SSP5-8.5 (high forcing) (2005-2025 to 2080-210

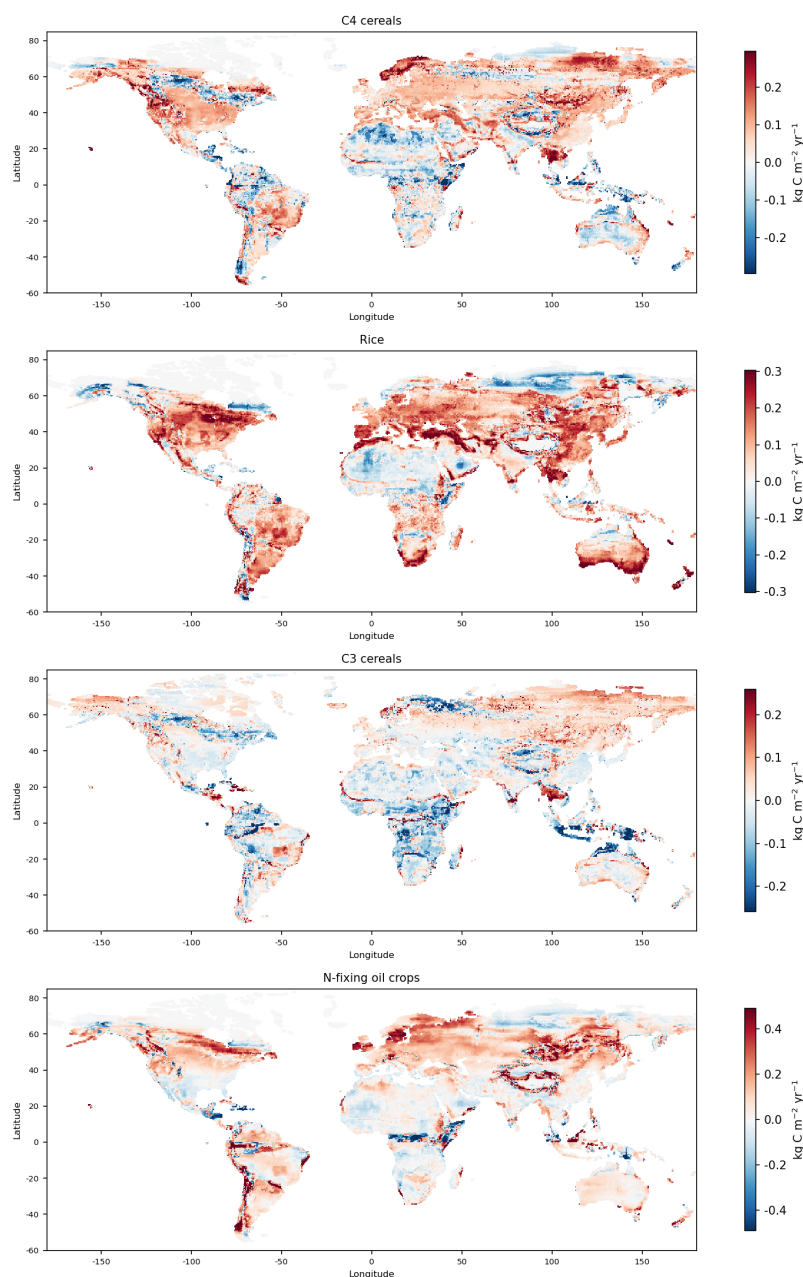


Figure 8. Difference in the present-day-to-end-of-century *change* in crop yield (IMOGEN-coupled minus ISIMIP-3b prescribed), for (a) SSP1-2.6 and (b) SSP5-8.5, as the difference between the two configurations' change from the present-day reference (2005-2025) to the end of century (2080-2100). Each panel set shows C4 cereals, rice, C3 cereals, and N-fixing oil crops. As for the carbon maps (Fig. 7), differencing the change removes the time-invariant baseline-climatology offset, so the maps show where the two configurations' yield responses differ; the difference is small and regionally mixed in sign. The



maps show the per-area change on all grid cells, whereas the aggregate statistics of Tables 13 and S2 are production-weighted by harvested area. Equivalent maps for the three intermediate scenarios are in the Supplement (Fig. S7); the corresponding absolute difference maps, which retain the baseline-climatology offset, are given for all five scenarios in the Supplement (Fig. S32).

3.4.3 Full-period trajectories

The carbon and nitrogen pools and fluxes are shown as global totals over the full 1901-2100 period for the two bracketing scenarios in Figs. 9 (SSP1-2.6) and 10 (SSP5-8.5). Net primary production and crop yields, being within-land-cover and per-crop quantities, are summarised instead by their mean statistics – end of century in Table 13 and Table S2, and over the consistent scenario period (2022-2100) in Tables S4 (yields, production-weighted by harvested area) and S5 (productivity, by land cover). These are also shown as scenario-period trajectories in the Supplement (Figs S10, S12). Throughout 1901-2100 the coupled configuration stores more terrestrial carbon and nitrogen than the prescribed-climate configuration. The superimposed emission-pathway component does not systematically erode the surplus over the scenario period (Sect. 2.4.6, 4.4). The mean-state offset and the scenario-period change are quantified in the Supplement (Sect. S3, Table S3).

Ecosystem-state trajectories 1901-2100, SSP1-2.6: ISIMIP-3b prescribed (solid) vs IMOGEN-coupled (dashed)

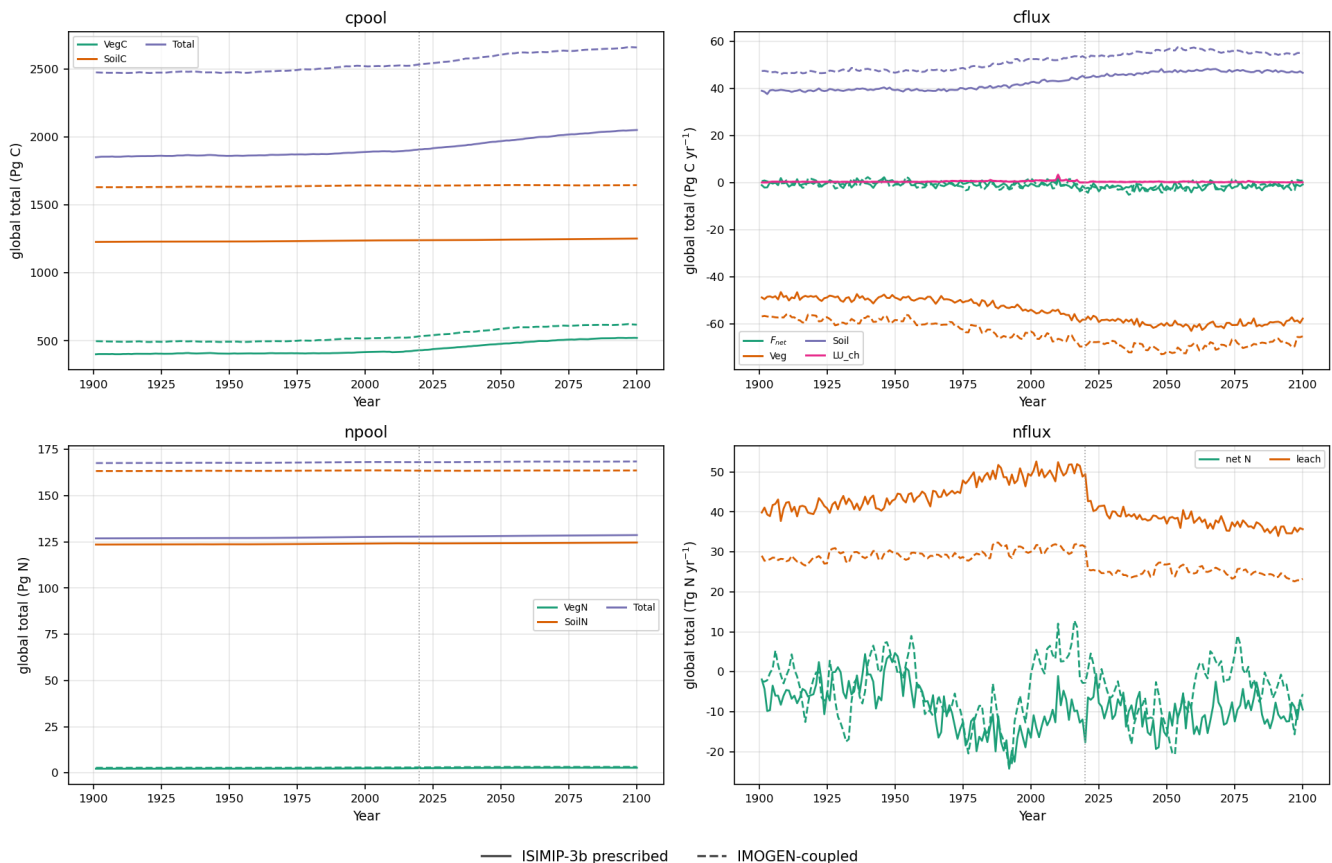




Figure 9. Global-total trajectories (1901-2100) of carbon pools (VegC, SoilC, total), carbon fluxes (F_{net} , vegetation, soil, land-use change), nitrogen pools (VegN, SoilN, total), and nitrogen fluxes (net N flux, leaching) under SSP1-2.6, for the ISIMIP-3b prescribed (solid) and IMOGEN-coupled (dashed) configurations. The dotted vertical line marks the 2020 historical-scenario land-use transition. The modest residual step at this transition in the cropland-related pools and nitrogen fluxes (crop-land vegetation carbon and nitrogen leaching) reflects the handover from the historical crop-management forcing (crop-type mix and fertiliser) to the time-varying PLUM scenario forcing in 2021, appearing near-identically in both configurations. It is a land-management-forcing feature rather than a coupling or climate signal (the land-use harmonisation follows Rabin et al. (2020); emission-side discontinuity noted in Sects. 2.3.2 and 4.3). Net primary production and crop yields, being within-land-cover and per-crop quantities, are shown separately as scenario-period trajectories in the Supplement (Figs S10, S12) and summarised as mean statistics (Tables 13, S2, S4, S5). The three intermediate scenarios (SSP2-4.5, SSP3-7.0, SSP4-6.0) are shown in Supplement Figs. S24-S26.

Ecosystem-state trajectories 1901-2100, SSP5-8.5: ISIMIP-3b prescribed (solid) vs IMOGEN-coupled (dashed)

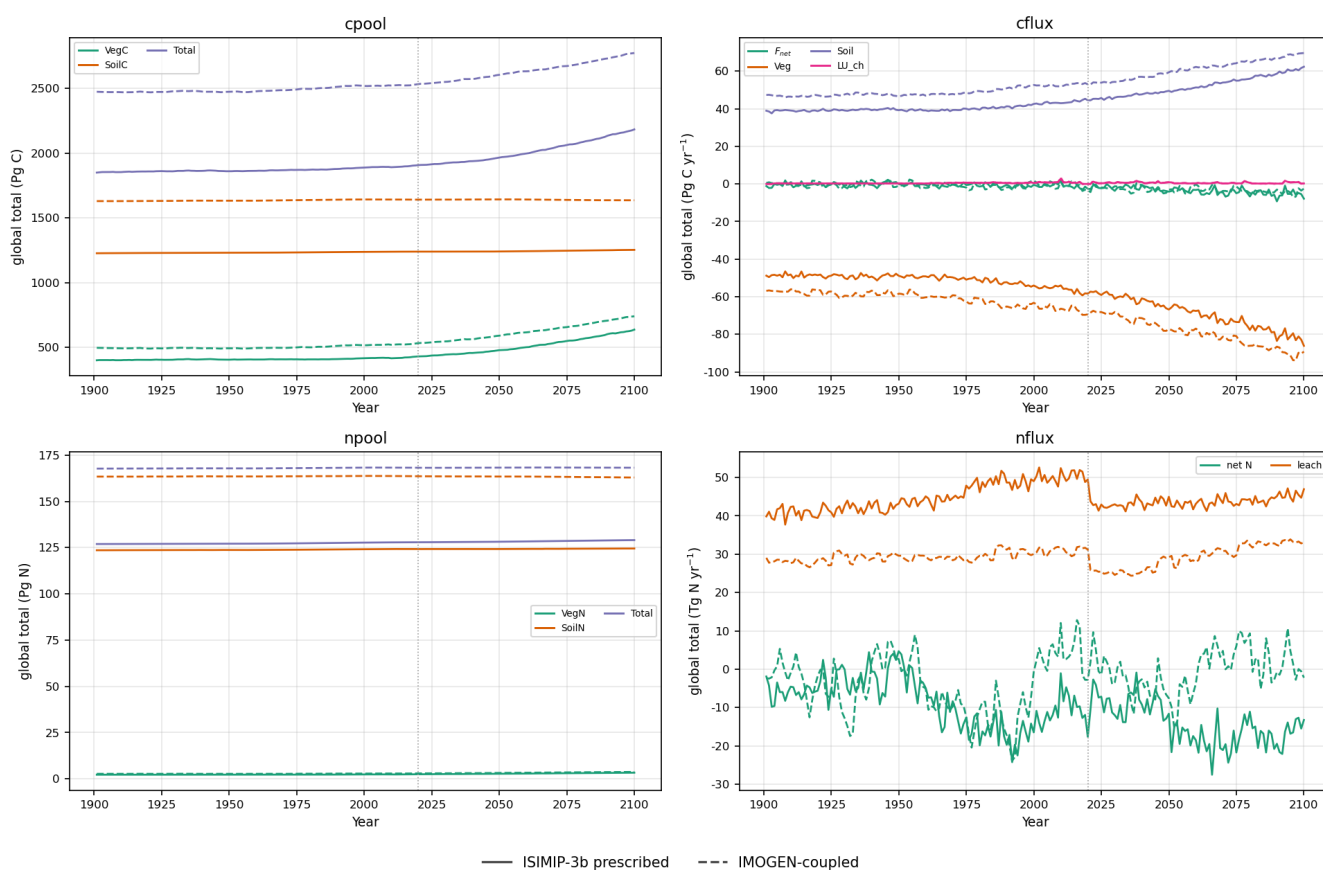


Figure 10. As Fig. 9, for SSP5-8.5.



4 Discussion

1070 4.1 Framework performance and evaluation

The three-tier evaluation (Sect. 3) establishes that the framework is fit for what it was designed to do, namely, to provide a comparative, traceable, bottom-up attribution of agricultural and land-management emissions to climate and ecosystem responses, while making its limitations explicit. At the inventory level (Tier-1), the bottom-up agricultural modules reproduce the FAOSTAT and EDGAR records with the nitrous-oxide aggregate and managed soils within the $\pm 20\%$ global-aggregate benchmark and the agricultural CH_4 aggregate at its upper edge (+19%, driven by the livestock sources). Every source category lies within the $\pm 20\text{--}50\%$ source-level uncertainty of the IPCC Tier-1 emission factors (IPCC, 2019). The consistent-sign high bias of the two livestock CH_4 sources against two independent inventories identifies it as a genuine methodological offset – IPCC regional default factors exceeding the country-specific values underlying the inventories – rather than random error, which is the expected and acceptable behaviour of a globally applied Tier-1 method.

1080 At the integrated level (Tier-2), the combined anthropogenic-plus-natural emissions match the observationally constrained global budgets to within a few per cent at the present day (CH_4 -5.1%, N_2O -2.2%, CO_2 +4.3%), and the prognostic concentrations reproduce the observed CO_2 , CH_4 , and N_2O records within their (uncertainty-scaled) benchmarks, with at most modest present-day biases (Sect. 3.2.2). The N_2O trajectory in particular is reproduced once the emulator’s single-box budget is supplied with the complete natural source (the LPJ-GUESS land-biosphere flux together with the ocean and non-land natural baseline), which is consistent with the prescribed CMIP6 non- CO_2 forcing that drives the coupled climate. At the climate level (Tier-3), the IMOGEN-coupled fields reproduce the ISIMIP-3b reference with high fidelity in both spatial pattern (e.g. near-surface-temperature spatial correlation of 0.98) and global-mean magnitude (temperature within about 0.3 K at all analysis windows), leaving a small residual regional mean-state difference that is near-neutral in the global mean (Huntingford et al., 2010; Zelazowski et al., 2018). An identical-emulator diagnostic shows the bottom-up emission-pathway feedback on temperature to be a cooling of 0.2 to 0.5 K and independent of the baseline choice (Sect. 2.4.6, 4.4). Taken together, the cascade shows that the coupled system is consistent with community estimates for the gases and fields that dominate the integrated forcing, with the residual biases reported for downstream interpretation.

4.2 Comparison with existing frameworks

LandSyMM occupies a distinct position among the model classes used to study land-climate interactions. Full-complexity Earth system models resolve the physical climate in detail but are typically driven by prescribed atmospheric concentrations or by emissions taken from integrated assessment models (IAMs). Their agricultural and land-management emissions are exogenous inputs rather than internally computed quantities, indicating that the bottom-up activity drivers cannot be varied or attributed within the model itself. IAM-plus-emulator frameworks such as MAGICC- or FaIR-based assessments (Nicholls et al., 2020; Smith et al., 2018) reproduce global forcing efficiently but represent the land system as aggregated economic sectors, without the spatially explicit, process-based biogeochemistry needed to resolve where and why land-based fluxes arise. Conversely, offline dynamic global vegetation model experiments – including the standard ISIMIP-3b LPJ-GUESS protocol used here



as the reference – are driven by prescribed bias-corrected climate and therefore cannot represent the feedback of their own land-based emissions onto that climate.

LandSyMM bridges these classes within a single, traceable process: spatially explicit bottom-up agricultural (IPCC Tier-1) and land-biosphere (LPJ-GUESS) emissions are integrated, passed through the embedded IMOGEN/FaIR emulator to generate a feedback climate, and returned to LPJ-GUESS to drive ecosystem responses. The contribution is not any individual component, as LPJ-GUESS (Smith et al., 2014), IMOGEN (Huntingford et al., 2010; Zelazowski et al., 2018), and the IPCC methodologies are all established, but their assembly into a reduced-complexity coupled system in which the land-system emission drivers are explicit, perturbable, and attributable end-to-end. The principal methodological contribution enabling this is the re-implementation of the Fortran IMOGEN emulator in C++ and its embedding directly within LPJ-GUESS (Sect. 2.4), which removes the file-based hand-off between separate models and makes the coupled loop a single executable. This design trades the physical fidelity of a full ESM for transparency and tractability: every step from activity data to ecosystem response can be inspected, and the cost of a coupled scenario is that of an emulator rather than a GCM.

4.3 Limitations and uncertainty

Several limitations warrant acknowledgement, and we report them consistent with the traceable design of the framework.

First, the Tier-1 emission factors are held static over the projection period (Sect. 2.4.5): the bottom-up modules scale present-day emission intensities by future activity (livestock numbers, fertiliser use, harvested area) but do not let the per-unit factors evolve with management, breeding, or technology. This is the dominant source of the biases reported in Sect. 3. It drives the systematic high bias of the agricultural CH₄ aggregate against FAOSTAT and EDGAR (+19%, from the two livestock sources; Sect. 3.1), because the IPCC regional default factors exceed the country-specific values underlying the inventories (Tubiello et al., 2013; Wolf et al., 2017). Allowing the emission factors to follow scenario-consistent intensity pathways is the highest-priority improvement for the bottom-up inventory.

Second, the prognostic N₂O concentration depends on the single-box FaIR budget being supplied with the *complete* natural N₂O source, because the budget carries no internal natural-source term of its own. The LPJ-GUESS land flux (soil plus fire) alone is a land-only quantity that omits the ocean and other non-land natural N₂O – of order 3-6 Tg N₂O yr⁻¹ of the 14-17 Tg yr⁻¹ total natural budget (consistent with Tian et al., 2024), making the framework rely on the complete natural source (the land-biosphere flux together with the ocean and non-land natural baseline) being carried into the budget, as in the trajectory evaluated here (Sect. 3.2.2). Supplied this way, the prognostic N₂O reproduces the observed record within benchmark (RMSD 5.6 ppb). Presently, this natural baseline is structurally prescribed as opposed to derived from a fully internal mechanistic natural N₂O source, so absolute N₂O forcing inherits the uncertainty of that baseline. Representing the full natural source mechanistically – rather than supplementing the land flux with a prescribed baseline – is a target for future work (Sect. 4.5).

Third, one methodological choice in the agricultural modules is documented as a known feature: the manure-management N₂O modules use 2006 IPCC Guidelines emission factors over the historical period (for consistency with the FAOSTAT inventory basis) and the 2019 Refinement factors for the projections, producing a modest step at the 2020 historical-scenario boundary (Sect. 2.3.2, 3.1). This is a deferred reconciliation rather than a conceptual gap.



Fourth, the coupled climate carries a residual regional mean-state difference relative to the ISIMIP-3b reference. The IMOGEN-coupled fields reproduce the reference spatial patterns with high fidelity (near-surface-temperature spatial correlation ≈ 0.98 ; Sect. 3.3) and the reference global-mean temperature to within about 0.3 K at all analysis windows, but the observation-based baseline climatology to which the pattern-scaled anomalies are referenced differs regionally from the ISIMIP-3b reference mean state; this regional mean-state difference is near-neutral in the global mean and is reported (Sect. 3.3). The identical-emulator diagnostic (Sect. 2.4.6, 4.4) shows the emission-pathway feedback on temperature to be a cooling of about 0.2 to 0.5 K, independent of the baseline choice. The evaluation also uses a single reference Earth system model (MRI-ESM2-0) for the ISIMIP-3b comparison, so the reported climate differences do not span the spread of the GCM patterns available to IMOGEN. Propagating a multi-pattern ensemble would bound the estimates.

Fifth, the coupling is sequential rather than within-timestep interactive: emissions are integrated and emulated, and the resulting climate is returned to drive ecosystems (Sect. 2.4). Given the multi-year averaging in the coupling and the emission-pathway feedback of a few tenths of a kelvin identified by the identical-emulator diagnostic (Sect. 4.4), a fully closed loop is not expected to change these results materially.

4.4 Implications for climate-ecosystem projections

The climate the coupling delivers to the ecosystem simulation reproduces the ISIMIP-3b reference closely in the global mean (within about 0.3 K at all analysis windows; Sect. 3.3), leaving a small residual regional mean-state difference. The framework's bottom-up integrated emissions diverge from the RCMIP trajectory that underlies the prescribed reference – by end of century the integrated CH_4 is higher by +14% to +71% and the net CO_2 source lower by 3.3-19.7 Gt $\text{CO}_2 \text{ yr}^{-1}$ across the scenarios relative to the scenario-baseline reference (Sect. 3.2.1; Fig. S21). We also isolate the resulting emission-pathway feedback using the identical-emulator diagnostic defined in Sect. 2.4.6. Because both configurations are built on the same underlying GCM (MRI-ESM2-0), the difference is not attributable to GCM identity. As reported in Sect. 3.3.1, this feedback takes the form of a cooling of 0.2 to 0.5 K, arising because the explicit LPJ-GUESS land sink lowers the integrated net CO_2 relative to the unmodified-RCMIP reference. The residual coupled-versus-prescribed climate impact difference is a regional mean-state offset arising from the observation-based baseline climatology (Sect. 3.3), near-neutral in the global mean. Propagating a multi-pattern IMOGEN ensemble and additional reference models (Sect. 4.3) would further constrain these estimates.

The ecosystem consequences of this coupling are quantified in Sect. 3.4. Because the coupled and prescribed configurations spin up under different observation-based baseline climatologies, they hold different absolute carbon pools: a persistent, forcing-independent offset of about +624 Pg C in total ecosystem carbon (about +4.3 kg C m^{-2}), concentrated in the boreal and cool-temperate soil and litter pools and present from the start of the simulation (Sect. 3.3-3.4). This offset is a baseline-climatology artefact rather than an emission-driven feedback. Compared on the meaningful basis of their changes over time, the two configurations track each other closely (the end-of-century carbon changes differ by an order of magnitude less than the offset; Table 13), and the genuine emission-pathway feedback, isolated by the identical-emulator diagnostic, is a cooling of 0.2 to 0.5 K. The framework's principal land-system contribution is therefore the traceable, process-based coupling and the explicit separation of this baseline mean-state offset from the emission-pathway feedback of a few tenths of a kelvin, rather



1170 than the magnitude of the carbon difference itself. Crop-yield differences are small and mixed in sign, and soil N₂O, wetland CH₄, and leaf area are modestly higher while runoff is lower. The two configurations agree closely on the spatial pattern of these responses ($r \approx 0.85$ - 0.86 for total ecosystem carbon), so the difference is expressed as a coherent change in magnitude on a shared geography rather than as a reorganisation of the ecosystem pattern.

This ecosystem offset is established over the historical period and is essentially independent of scenario forcing (Sect. S3.2, Table S3), rather than a warming-driven response. Propagating the identical-emulator partition through to the ecosystem level such that the emission-pathway feedback on ecosystem state is reported separately from this baseline mean-state offset – is deferred to future work (Sect. 4.5).

4.5 Future directions

Future development priorities follow from the limitations above. The foremost is (i) replacing the static Tier-1 emission factors with scenario-consistent, time-evolving emission intensities – for example dynamic livestock-productivity and fertiliser-efficiency pathways drawn from the IAMs that underpin the SSPs (O'Neill et al., 2016) – which would directly address the agricultural CH₄ high bias. Distinct from this, (ii) constraining the natural N₂O budget more tightly: the LPJ-GUESS soil-and-fire source is resolved internally, whereas the non-land (including ocean) natural term is at present prescribed as a fixed baseline of ≈ 3 - $6 \text{ Tg N}_2\text{O yr}^{-1}$ (Tian et al., 2024) (Sect. 4.3); a tighter observational constraint on that residual term would reduce the framework's reliance on an external baseline for absolute N₂O forcing. Further priorities are (iii) reconciling the documented 2006/2019 manure-N₂O emission-factor discontinuity at the historical-scenario join (Sect. 4.3); (iv) propagating a multi-pattern IMOGEN ensemble (for example the 22-GCM set) and additional reference Earth system models to bound the climate-feedback estimates rather than relying on a single pattern and reference; (v) replacing the present land-biosphere N₂O representation with the dedicated process-based nitrification-denitrification soil-N₂O module recently developed for LPJ-GUESS (Ma et al., 2022), which is not yet integrated into the coupled framework and is expected to improve the mechanistic fidelity of the land N₂O source; and (vi) propagating the identical-emulator partition – already applied at the climate level (Sect. 4.4), where it resolves the emission-pathway feedback on temperature as a cooling of a few tenths of a kelvin – through to the ecosystem response, so that the genuine coupling feedback on ecosystem state is reported separately from the baseline mean-state offset.

1195 5 Conclusions

We have presented the IMOGEN-coupled configuration of LandSyMM: a reduced-complexity framework that derives atmospheric forcing from spatially explicit, bottom-up land-management emissions and returns the emulated climate to drive ecosystem dynamics, closing the link from agricultural management, through emissions and climate, to ecosystem response within a single traceable executable. The methodological advance that makes this tractable is the re-implementation of the Fortran IMOGEN emulator in C++ and its embedding directly within LPJ-GUESS, which replaces the file-based hand-off between separate models with one coupled run at emulator cost.



The principal value of the framework lies less in the magnitude of any single coupled-versus-prescribed difference than in its capacity to isolate and attribute the constituent signals. The higher absolute terrestrial carbon storage of the coupled configuration (a baseline offset of about +624 Pg C, or about +4.3 kg C m⁻²) is shown, by decomposition and by an identical-emulator diagnostic, to be a persistent mean-state artefact that follows from referencing the emulated anomalies to an observation-based baseline climatology rather than to the ISIMIP-3b reference mean state; it is present from the start of the simulation rather than accruing with forcing, and the two configurations' changes over time track each other closely (Table 13). The genuine bottom-up emission-pathway feedback on temperature, by contrast, is a cooling, independent of the baseline choice. Relative to the same scenarios driven by the unmodified RCMIP anthropogenic emissions and the default FaIR natural baseline, the framework's integrated bottom-up emissions – with the IPCC Tier-1 agricultural and LPJ-GUESS land-biosphere terms replacing the corresponding components – lower projected global-land-mean warming by about 0.2 to 0.5 K (largest, about 0.5 K, under the low-forcing SSP1-2.6), because the explicit terrestrial CO₂ sink outweighs the higher agricultural CH₄. This is a climatically non-trivial magnitude, and one that runs counter to any expectation that more complete land-management accounting would increase projected warming. Separating a structural baseline offset from a real emission-pathway signal of a few tenths of a kelvin in this way is precisely the controlled attribution the framework was designed to enable. Taken together, these results establish LandSyMM-IMOGEN as a computationally tractable alternative to both full Earth system models and aggregated integrated-assessment frameworks for studying how socioeconomically driven, bottom-up land-management emissions propagate through climate to ecosystems.

Appendix A

Appendix A: IPCC (2019) Tier-1 parameter tables for agricultural emissions

This appendix provides the regional parameter values used in the IPCC Tier-1 agricultural emission modules described in Sect. 2.2. Values are drawn from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Gavrilova et al., 2019), Volume 4, Chapter 10 (Emissions from Livestock and Manure Management). Parameters are held static throughout the 2020-2100 projection period unless otherwise noted.

Table A1: Enteric fermentation emission factors (EF) for Tier-1 method

Units: kg CH₄ head⁻¹ yr⁻¹

Source: IPCC (2019) Table 10.10 and Table 10.11

Table A1.1: Cattle and buffalo (Table 10.11)

Region	Dairy Cattle	Other Cattle	Buffalo
North America	128	53	–
Western Europe	126	52	–
Eastern Europe	111	56	–
Oceania	101	61	–



Region	Dairy Cattle	Other Cattle	Buffalo
Latin America	72	56	55
Africa	46	31	55
Middle East	70	32	55
Asia	68	47	55
Indian Subcontinent	56	47	55

Notes:

- 1230 - Dairy cattle: mature females producing milk for human consumption
 - Other cattle: all non-dairy cattle including beef cattle, draft animals, growing cattle
 - Buffalo primarily relevant for Asia, Indian Subcontinent, Africa, Latin America

Table A1.2: Other livestock (Table 10.10)

Livestock Category	Developed Countries	Developing Countries
Sheep	8	5
Goats	5	5
Camels	46	46
Horses	18	18
Mules and Asses	10	10
Swine	1.5	1
Poultry	Neg.	Neg.

Table A2: Volatile solid (VS) excretion rates

1235 Units: kg VS (1000 kg animal mass)⁻¹ day⁻¹

Source: IPCC (2019) Table 10.13A

Livestock Category	VS Excretion Rate	Uncertainty Range
Dairy Cattle	7.5	5.4-9.8
Other Cattle	5.7	4.6-7.1
Buffalo	7.7	6.0-9.5
Sheep	8.2	5.1-12.3
Goats	9	6.0-13.0
Market Swine	4.5	2.7-7.2
Breeding Swine	2.6	1.6-4.2



Livestock Category	VS Excretion Rate	Uncertainty Range
Layers	10	6.5-14.0
Broilers	10	6.5-14.0
Turkeys	8.5	5.5-12.0
Horses	5.65	4.0-7.5
Mules and Asses	4.5	3.2-6.0

Notes:

- Values represent aggregated global averages
- Regional variation captured in Tier 1a approach using productivity-specific values (Tables 10A.1-10A.4)
- Annual VS = VS rate $\times$ TAM $\times$ 365 / 1000

Table A3: Nitrogen (N) excretion rates

Units: kg N (1000 kg animal mass)⁻¹ day⁻¹

Source: IPCC (2019) Table 10.19

Livestock Category	N Excretion Rate	Uncertainty Range
Dairy Cattle	0.44	0.31-0.62
Other Cattle	0.33	0.24-0.45
Buffalo	0.32	0.23-0.44
Sheep	0.85	0.55-1.27
Goats	1.37	0.90-2.05
Market Swine	0.42	0.25-0.67
Breeding Swine	0.46	0.28-0.74
Layers	0.83	0.54-1.24
Broilers	1.1	0.72-1.65
Turkeys	0.74	0.48-1.11
Horses	0.3	0.19-0.45
Mules and Asses	0.3	0.19-0.45

Notes:

- Values represent aggregated global averages
- For Tier-2: Nex = Nintake $\times$ (1 – Nretention)
- Annual N excretion = N rate $\times$ TAM $\times$ 365 / 1000

Table A4: Typical animal mass (TAM)



Units: kg head⁻¹

1250 Source: IPCC (2019) Table 10A.5

Livestock Category	North America	Western Europe	Eastern Europe	Oceania	Latin America	Africa	Middle East	Asia	Indian Subcontinent
Dairy Cattle	604	600	475	500	400	275	275	300	275
Other Cattle	389	420	350	330	305	200	200	250	200
Buffalo	–	–	–	–	380	380	380	380	380
Sheep	50	48	40	45	32	28	28	32	28
Goats	40	38	35	35	30	25	25	30	25
Market Swine	82	80	65	70	50	50	50	50	50
Breeding Swine	175	180	145	150	100	80	80	90	80
Layers	2.5	2.3	2.2	2.2	2	1.8	1.8	2	1.8
Broilers	2.5	2.3	2.2	2.2	2	1.8	1.8	2	1.8
Turkeys	8.5	9	7.5	8	6	5	5	5.5	5
Horses	450	400	350	380	300	250	250	280	250

Notes:

- "-" indicates livestock category not relevant for region
- Values represent population-weighted annual averages
- Poultry masses represent average over production cycle

1255 **Table A5: Maximum methane producing capacity (B₀)**

Units: m³ CH₄ (kg VS)⁻¹

Source: IPCC (2019) Table 10.16A

Livestock Category	B ₀	Uncertainty Range
Dairy Cattle	0.24	0.17-0.32
Other Cattle	0.19	0.13-0.26
Buffalo	0.1	0.07-0.14
Market Swine	0.45	0.32-0.60



Livestock Category	B ₀	Uncertainty Range
Breeding Swine	0.45	0.32-0.60
Sheep	0.19	0.13-0.26
Goats	0.18	0.12-0.25
Layers (dry)	0.39	0.28-0.52
Layers (wet)	0.39	0.28-0.52
Broilers	0.36	0.25-0.48
Turkeys	0.36	0.25-0.48
Horses	0.3	0.21-0.40
Mules and Asses	0.33	0.23-0.44

Notes:

- B₀ depends on feed composition and digestibility
- Values represent maximum potential under complete anaerobic decomposition
- Actual CH₄ production = B₀ × MCF

Table A6: Methane conversion factors (MCF) by manure management system and climate zone

Units: Fraction (0-1) or Percent (%)

Source: IPCC (2019) Table 10.17

Note: the IPCC Table 10.17 methane conversion factors are binned by annual mean temperature (Cool/Temperate/Warm) only; the moisture-qualified IPCC climate zones assigned in Table 3 (used for the other emission factors) map onto these bins through their temperature component.

Manure Management System	Cool (<15°C)	Temperate (15-25°C)	Warm (>25°C)
LIQUID SYSTEMS			
Anaerobic lagoon	66-73	74-79	78-80
Liquid/Slurry (no crust)	17-25	35-48	55-65
Liquid/Slurry (with crust)	10-17	18-30	30-40
SOLID SYSTEMS			
Solid storage	2	4	5
Dry lot	1	1.5	2
PASTURE/RANGE/Paddock			
Deposited on pasture	1	1.5	2
TREATMENT SYSTEMS			



Manure Management System	Cool (<15°C)	Temperate (15-25°C)	Warm (>25°C)
Composting (in-vessel)	0.5	0.5	0.5
Composting (static pile)	0.5	0.5	0.5
Composting (intensive windrow)	0.5	1	1.5
Composting (passive windrow)	0.5	1	1
Anaerobic digester	1-10	1-10	1-10
OTHER			
Burned for fuel	10	10	10
Daily spread	0.1	0.5	1
Pit storage <1 month	3	3	3
Pit storage >1 month	17-25	35-48	55-65
Deep bedding (no mixing)	17	25	44
Deep bedding (active mixing)	3	3	3
Poultry with litter	1.5	1.5	1.5
Poultry without litter	1.5	1.5	1.5

Notes:

- Climate zones based on mean annual temperature
- Ranges reflect uncertainty and regional variation
- For liquid systems, MCF increases with temperature and retention time

Table A7: Direct N₂O emission factors for manure management systems

Units: kg N₂O-N (kg N excreted)⁻¹

Source: IPCC (2019) Table 10.21

Manure Management System	EF ₃	Uncertainty Range
Anaerobic lagoon	0	–
Liquid/Slurry	0.005	0.0025-0.01
Solid storage	0.005	0.0025-0.01
Dry lot	0.02	0.01-0.05
Pasture/Range/Paddock (cattle)	0.006	0.002-0.01



Manure Management System	EF ₃	Uncertainty Range
Pasture/Range/Paddock (sheep)	0.003	0.001-0.006
Pasture/Range/Paddock (other)	0.005	0.002-0.01
Composting (in-vessel)	0.006	0.003-0.012
Composting (static pile)	0.006	0.003-0.012
Composting (intensive windrow)	0.1	0.05-0.15
Composting (passive windrow)	0.01	0.005-0.02
Anaerobic digester	0	–
Burned for fuel	0	–
Daily spread	0	–
Deep bedding (cattle/swine)	0.01	0.005-0.02
Deep bedding (poultry)	0.001	0.0005-0.002
Poultry with litter	0.001	0.0005-0.002
Poultry without litter	0.001	0.0005-0.002

1275 Notes:

- EF₃ represents direct N₂O emissions from manure management
- Values exclude indirect emissions from volatilisation and leaching
- Conversion: kg N₂O = kg N₂O-N × 44/28

Table A8: Nitrogen loss fractions for volatilisation and leaching

1280 Source: IPCC (2019) Table 10.22

Table A8.1: Volatilisation fractions (FracGasMS)

Units: kg NH₃-N + NO_x-N (kg N excreted)⁻¹

Manure Management System	Cattle	Swine	Poultry	Sheep/Goats	Other
Anaerobic lagoon	0.35	0.4	–	–	0.3
Liquid/Slurry	0.3	0.35	–	–	0.25
Solid storage	0.3	0.35	0.4	0.12	0.25
Dry lot	0.3	0.35	–	–	0.25
Pasture/Range/Paddock	0.21	–	–	0.12	0.2
Composting	0.4	0.45	0.5	0.3	0.35
Anaerobic digester	0.05	0.05	–	–	0.05
Deep bedding	0.3	0.35	0.4	–	0.25
Poultry with litter	–	–	0.4	–	–



Manure Management System	Cattle	Swine	Poultry	Sheep/Goats	Other
Poultry without litter	–	–	0.55	–	–

Table A8.2: Leaching fractions (FracLeachMS)

Units: kg N (kg N excreted)^{−1}

Manure Management System	Default Value	Range
Anaerobic lagoon	0	0-0.05
Liquid/Slurry	0	0-0.02
Solid storage	0	0-0.10
Dry lot	0	0-0.15
Pasture/Range/Paddock	0	0-0.30
Other systems	0	0-0.10

1285 Notes:

- Leaching is assumed negligible (0) for most managed systems
- Non-zero values may apply in regions with high precipitation
- "-" indicates system not typically used for that livestock category

Table A9: Animal waste management system (AWMS) regional distributions – cattle and buffalo

1290 Units: Fraction (sums to 1.0 within each region × livestock combination)

Source: IPCC (2019) Table 10A.6

Table A9.1: Dairy cattle

Region	Pasture/Range	Solid Storage	Liquid/Slurry	Lagoon	Dry Lot	Daily Spread	Other
North America	0.2	0.1	0.3	0.3	0.05	0.05	0
Western Europe	0.25	0.25	0.4	0	0.05	0.05	0
Eastern Europe	0.2	0.4	0.2	0.05	0.1	0.05	0
Oceania	0.85	0.05	0.05	0.05	0	0	0
Latin America	0.75	0.1	0.05	0.05	0.05	0	0



Region	Pasture/Range	Solid Storage	Liquid/Slurry	Lagoon	Dry Lot	Daily Spread	Other
Africa	0.8	0.1	0.02	0	0.05	0	0.03
Middle East	0.5	0.3	0.05	0	0.1	0	0.05
Asia	0.4	0.3	0.1	0.05	0.1	0	0.05
Indian Sub-continent	0.5	0.25	0.05	0	0.1	0	0.1

Table A9.2: Other cattle

Region	Pasture/Range	Solid Storage	Liquid/Slurry	Lagoon	Dry Lot	Daily Spread	Other
North America	0.6	0.05	0.05	0.05	0.2	0.05	0
Western Europe	0.65	0.15	0.1	0	0.05	0.05	0
Eastern Europe	0.55	0.25	0.05	0	0.1	0.05	0
Oceania	0.95	0.02	0.01	0.01	0.01	0	0
Latin America	0.9	0.05	0.02	0.01	0.02	0	0
Africa	0.9	0.05	0.01	0	0.02	0	0.02
Middle East	0.7	0.15	0.03	0	0.1	0	0.02
Asia	0.7	0.15	0.05	0.02	0.05	0	0.03
Indian Sub-continent	0.8	0.1	0.02	0	0.05	0	0.03

Table A9.3: Buffalo

Region	Pasture/Range	Solid Storage	Liquid/Slurry	Daily Spread	Other
Asia	0.65	0.2	0.05	0.05	0.05
Indian Subcontinent	0.7	0.15	0.05	0.05	0.05
Latin America	0.85	0.1	0.02	0.03	0
Africa	0.85	0.1	0.02	0.03	0



Region	Pasture/Range	Solid Storage	Liquid/Slurry	Daily Spread	Other
Middle East	0.7	0.2	0.05	0.05	0

1295 **Table A10: Animal waste management system (AWMS) regional distributions – swine**

Units: Fraction (sums to 1.0 within each region)

Source: IPCC (2019) Table 10A.7

Region	Pasture/Range	Solid Storage	Liquid/Slurry	Lagoon	Pit Storage	Deep Bedding	Other
North America	0	0.05	0.4	0.35	0.15	0.05	0
Western Europe	0	0.25	0.6	0	0.1	0.05	0
Eastern Europe	0.05	0.4	0.3	0.05	0.15	0.05	0
Oceania	0.1	0.2	0.4	0.2	0.05	0.05	0
Latin America	0.3	0.3	0.15	0.1	0.1	0.05	0
Africa	0.5	0.3	0.05	0.02	0.1	0.03	0
Middle East	0.3	0.4	0.1	0.05	0.1	0.05	0
Asia	0.25	0.3	0.2	0.1	0.1	0.05	0
Indian Sub-continent	0.4	0.35	0.1	0.05	0.05	0.05	0

Table A11: Animal waste management system (AWMS) regional distributions – sheep and goats

Units: Fraction (sums to 1.0 within each region)

Source: IPCC (2019) Table 10A.8

Table A11.1: Sheep

Region	Pasture/Range	Solid Storage	Dry Lot	Daily Spread	Other
North America	0.85	0.05	0.05	0.05	0
Western Europe	0.75	0.15	0.05	0.05	0
Eastern Europe	0.65	0.25	0.05	0.05	0
Oceania	0.95	0.03	0.01	0.01	0

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Region	Pasture/Range	Solid Storage	Dry Lot	Daily Spread	Other
Latin America	0.9	0.05	0.03	0.02	0
Africa	0.9	0.05	0.03	0.02	0
Middle East	0.7	0.2	0.05	0.05	0
Asia	0.8	0.1	0.05	0.05	0
Indian Subcontinent	0.85	0.08	0.05	0.02	0

Table A11.2: Goats

Region	Pasture/Range	Solid Storage	Dry Lot	Daily Spread	Other
North America	0.85	0.05	0.05	0.05	0
Western Europe	0.7	0.2	0.05	0.05	0
Eastern Europe	0.6	0.3	0.05	0.05	0
Oceania	0.95	0.03	0.01	0.01	0
Latin America	0.9	0.05	0.03	0.02	0
Africa	0.9	0.05	0.03	0.02	0
Middle East	0.7	0.2	0.05	0.05	0
Asia	0.8	0.1	0.05	0.05	0
Indian Subcontinent	0.85	0.08	0.05	0.02	0

Table A12: Animal waste management system (AWMS) regional distributions – poultry

Units: Fraction (sums to 1.0 within each region × poultry type combination)

Source: IPCC (2019) Table 10A.9

Table A12.1: Layers

Region	With Litter (dry)	Without Litter (high-rise)	Liquid/Slurry	Pasture/Range	Other
North America	0.15	0.6	0.15	0.05	0.05
Western Europe	0.5	0.3	0.1	0.05	0.05
Eastern Europe	0.4	0.4	0.1	0.05	0.05
Oceania	0.4	0.4	0.1	0.05	0.05
Latin America	0.4	0.35	0.1	0.1	0.05
Africa	0.3	0.2	0.05	0.4	0.05
Middle East	0.45	0.35	0.1	0.05	0.05



Region	With Litter (dry)	Without Litter (high-rise)	Liquid/Slurry	Pasture/Range	Other
Asia	0.35	0.4	0.1	0.1	0.05
Indian Subcontinent	0.3	0.3	0.1	0.25	0.05

Table A12.2: Broilers

Region	With Litter	Without Litter	Pasture/Range	Other
North America	0.95	0	0	0.05
Western Europe	0.9	0.05	0	0.05
Eastern Europe	0.85	0.1	0	0.05
Oceania	0.9	0.05	0	0.05
Latin America	0.8	0.1	0.05	0.05
Africa	0.5	0.1	0.35	0.05
Middle East	0.8	0.1	0.05	0.05
Asia	0.7	0.15	0.1	0.05
Indian Subcontinent	0.6	0.15	0.2	0.05

Table A13: Managed soils N₂O emission factors (Chapter 11)

Source: IPCC (2019) Table 11.1

1310 **Table A13.1: Direct emission factor (EF₁) for mineral fertiliser and organic amendments**

Units: kg N₂O-N / kg N applied

Climate Zone	EF ₁	Uncertainty Range
Aggregated (all climates)	0.01	0.001-0.018
Wet climate	0.016	0.013-0.019
Dry climate	0.005	0.000-0.011

Table A13.2: Emission factors for animal manure applied to soils



Parameter	Description	Value	Uncertainty
EF ₄	Volatilisation pathway (kg N ₂ O-N / kg NH ₃ -N + NO _x -N)	0.01	0.002-0.05
EF ₅	Leaching/runoff pathway (kg N ₂ O-N / kg N leached)	0.011	0.000-0.073
FracGASF	Fraction volatilised (synthetic fertiliser)	0.11	0.03-0.30
FracGASM	Fraction volatilised (organic amendments)	0.21	0.05-0.50
FracLEACH	Fraction leached (wet climates)	0.24	0.01-0.73

Table A14: Rice cultivation CH₄ emission parameters

Source: IPCC (2019) Table 5.11 and associated text

1315 **Baseline Emission Factor**

Parameter	Value	Description
EF _c	1.30 kg CH ₄ ha ⁻¹ day ⁻¹	Continuously flooded, no organic amendments (global default)

Note: 1.30 is the IPCC global default baseline factor; the model applies the region-specific *EF_c* values of Table 4 (IPCC Table 5.11), which supersede this global default.

Water Regime Scaling Factors (SF_w)

Water Regime	SF _w	Description
Continuously flooded	1	Baseline (no drainage)
Intermittent (single aeration)	0.6	Single drainage during growing season
Intermittent (multiple aeration)	0.52	Multiple drainage periods (AWD)
Rainfed (flood prone)	0.8	Subject to uncontrolled flooding
Rainfed (drought prone)	0.4	Subject to periodic water stress
Deep water (>50 cm)	0.8	Reduced methanogenesis at depth
Upland (non-flooded)	0	No anaerobic conditions

Pre-season & Organic Amendment Factors



Condition/Amendment	Factor	Description
PRE-SEASON (SFp)		
Straw incorporated (<30 days)	1	Recent incorporation
Straw incorporated (>30 days)	0.29	Long pre-season incorporation
Straw removed	1	Baseline
Green manure	1.22	Increased organic inputs
Fallow	1	No recent amendments
ORGANIC AMENDMENT (CFoa)		
Straw (short aerobic pretreatment)	1	Baseline
Straw (long aerobic pretreatment)	0.29	Extended decomposition
Farm yard manure	0.14	Composted manure
Compost	0.05	Fully composted
Green manure	0.5	Fresh biomass

1320 Unit conversions

Mass Conversions

Conversion	Factor	Notes
N ₂ O-N → N ₂ O	× 44/28	Molecular weight ratio
C → CO ₂	× 44/12	Molecular weight ratio
C → CH ₄	× 16/12	Molecular weight ratio
kg → Tg	× 10 ⁻⁹	–
kg → Gg	× 10 ⁻⁶	–

Appendix B

Appendix B: Component model descriptions

This appendix provides full descriptions of the three established component models integrated within the LandSyMM-
 1325 IMOGEN framework (Sect. 2.1): the LPJ-GUESS dynamic global vegetation model (B1), the PLUM v2 land-use model (B2),
 and the IMOGEN climate emulator (B3).

B1 LPJ-GUESS (dynamic global vegetation model)

LPJ-GUESS is an individual-based, spatially explicit dynamic global vegetation model (DGVM) that mechanistically simulates terrestrial physiological and demographic responses to biogeophysical and biogeochemical processes (Lindeskog et



1330 al., 2021; Smith et al., 2014). The model captures the establishment, growth, and mortality of individual plants, representing competition for light, water, and soil resources among co-occurring plant functional types (PFTs). Within a simulated area or "patch," woody vegetation is organised into cohorts – groups of same-aged individuals of a plant functional type – while grasses and crops are represented as area-averaged populations rather than as cohorts; this supports a detailed representation of population and community structure, carbon assimilation, and ecosystem turnover. Vegetation assimilates atmospheric CO₂ on a daily timestep, with productivity governed by photosynthetically active radiation (PAR) absorption, temperature, and water availability, and regulated by nitrogen limitation and the optimal redistribution of leaf nitrogen across the canopy (Smith et al., 2014). Population dynamics and disturbances – including wildfires and background (stochastic) mortality – are represented so as to restart successional cycles and maintain ecological realism (Smith et al., 2014). LPJ-GUESS has been extensively evaluated against eddy-covariance flux tower observations, forest inventory data, and satellite-derived vegetation products across multiple biomes (Smith et al., 2014).

The model's process-based architecture includes a representation of managed land and agricultural systems. LPJ-GUESS represents croplands and pastures as specific "stands" that distinguish various rainfed and irrigated crop functional types (CFTs), including spring and winter C3 cereals, C4 cereals, and rice (Lindeskog et al., 2013; Olin et al., 2015b), as well as nitrogen-fixing soybean and pulses (Ma et al., 2022). The growth of these CFTs incorporates CO₂ fertilisation and nitrogen limitation, enabling the model to simulate how enhanced water-use efficiency and reduced photorespiration can improve productivity under changing atmospheric conditions. Process-based CFT growth mechanisms ensure that plant water stress and nutrient availability directly mediate the final harvested biomass (Olin et al., 2015b). LPJ-GUESS has been evaluated for its capability to representatively simulate yield responses to changes in, e.g., irrigation water demand and supply, accounting for plant water stress, as well as yield responses to increased atmospheric CO₂ concentrations (Ma et al., 2022; Olin et al., 2015a, b). The combination of demographic realism and biogeochemical process representation makes LPJ-GUESS a central tool for mapping PLUM agricultural activity data to spatially explicit biophysical emission intensities within the LandSyMM framework.

B2 PLUM v2 (land use model)

The Parsimonious Land Use Model version 2 (PLUM v2) generates the spatial and temporal trajectories of land use and agricultural management that drive our methane and nitrous oxide calculations (Alexander et al., 2018). PLUM operates at a 0.5° spatial resolution to project future land use and management (LUM), such as nitrogen fertiliser and irrigation intensity, and land cover change (LCC), including cropland and pasture fractions. These trajectories are determined by a combination of grid-cell level productivity derived from the LPJ-GUESS ecosystem model, global trends in supply and demand for agricultural and forest resources and their trade, ensuring that the activity data – such as rice area or fertiliser application rates – reflect both local biophysical constraints and global market shifts (Engström et al., 2016; Rabin et al., 2020).

PLUM simulates agricultural production across six primary crop types – C3 cereals, C4 cereals, rice, oil crops, pulses, and starchy roots – and two broad animal categories, encompassing monogastrics (swine and poultry) and ruminants (cattle, sheep, and goats). Future food demand is determined endogenously from country-level population and GDP scenarios using a mod-



ified, implicit, directly additive demand system (MAIDADS) that represents the income-dependence of dietary composition
 (Gouel and Guimbard, 2019; Preckel et al., 2010). Relying on a least-cost optimisation approach within a unique disequilibrium
 framework, PLUM calculates how domestic production and international trade satisfy this demand. Unlike traditional
 general equilibrium models, this approach accommodates short-term resource surpluses and deficits, capturing real-world market
 imbalances where global supply and demand frequently enter non-equilibrium states (Alexander et al., 2018).

Management inputs such as nitrogen fertiliser and irrigation are modelled using yield tables generated from factorial ex-
 periments in LPJ-GUESS, which PLUM interpolates into a continuous range of gridded application rates (Alexander et al.,
 2018). This intensification follows a diminishing-returns function, where yield gains approach an asymptote at higher intensity
 levels, providing a realistic cap on productivity and fertiliser use (Olin et al., 2015b). PLUM calculates livestock activity data
 by converting traded commodities into primary product equivalents through commodity processing trees. It allocates feed to
 monogastrics first, with remnant feed and all country-level pasture area allocated to ruminants. These resulting trade flows and
 feed requirements are converted into historical and future livestock counts and land-use distributions, directly informing our
 manure management and enteric fermentation modules (Alexander et al., 2017).

By coupling biophysical constraints with economic optimisation, PLUM satisfies demand while considering commodity
 prices and management costs, including a factor for other management variables such as pesticide use and mechanisation. For
 the 2020-2100 simulation period, PLUM benchmarks its 2020 land cover change to the HILDA+ (Historic Land Dynamics As-
 sessment) baseline (Winkler et al., 2021). While the model calculates land-use areas as net changes to maintain computational
 efficiency – tracking net rather than gross land-cover transitions – it provides the spatially explicit outputs necessary for a full
 GHG simulation, including gridded maps of crop distribution, irrigation intensity, and nitrogen application rates (Rabin et al.,
 2020).

B3 IMOGEN (climate emulator)

The Integrated Model Of Global Effects of climatic aNomalies (IMOGEN) serves as an intermediate-complexity climate emu-
 lator designed to bridge the computational gap between high-resolution General Circulation Models (GCMs) and the require-
 ment for rapid, multi-scenario projections of land-atmosphere interactions (Huntingford et al., 2010). At its core, IMOGEN
 uses a pattern-scaling approach to derive spatially and temporally explicit climate responses from global greenhouse-gas emis-
 sions (Zelazowski et al., 2018). This methodology relies on empirical observations of near-linear relationships between local
 meteorological variations and the global mean temperature change over land. By calibrating these linear responses against a
 suite of GCMs – the 22-GCM CMIP3-generation pattern set of Zelazowski et al. (2018), the later 34-model CMIP5 set of
 Comyn-Platt et al. (2018), and, for the present work, a CMIP6 set (including MRI-ESM2-0) derived by G. Munday (Mathison
 et al., 2025) – IMOGEN can emulate a wide range of climate sensitivities and regional patterns, enabling climate projections
 that would otherwise require multi-year GCM integrations to be completed in minutes (Huntingford et al., 2010; Zelazowski
 et al., 2018).

The climate response is initiated by a global energy balance model (EBM) that translates changes in atmospheric radiative
 forcing into a global mean temperature anomaly. In our coupled framework, we integrate the Finite Amplitude Impulse Re-



sponse (FaIR v1.3) (Smith et al., 2018) model as the effective radiative forcing (ERF) module upstream of IMOGEN's energy balance model. This integration – which extends the standard IMOGEN configuration of Huntingford et al. (2010) and follows the approach implemented in the PRIME framework (Mathison et al., 2025) – enables emissions-driven operation: FaIR converts annual mass-based GHG emission inputs (CO_2 , CH_4 , and N_2O) into time-evolving atmospheric concentrations and effective radiative forcings – the emissions-to-concentration conversion representing the atmospheric loss processes (lifetimes) of CH_4 and N_2O and the CO_2 carbon-cycle box model – which IMOGEN's energy balance model then translates into a global mean temperature anomaly. This is necessary in the LandSyMM context because our bottom-up modelling pipeline produces annual emission totals by gas, not prescribed concentrations, necessitating an explicit emissions-to-concentrations conversion step before pattern scaling can be applied. The EBM accounts for the thermal inertia of the ocean using a simple diffusion-loss formulation, effectively modelling the temporal lag between atmospheric forcing and the thermal response of the Earth system (Huntingford et al., 2010). This emissions-driven configuration provides the basis for representing global carbon-cycle interactions, in which land-based emissions drive a climate response that can, in turn, modulate the future land sink – realised in the present framework through the sequential coupling described in Sect. 2.4.

For every grid point and month spanning from the pre-industrial period to the future, IMOGEN employs monthly regressions against the global land temperature anomaly to determine corresponding changes in the principal meteorological variables. This includes temperature as well as precipitation, specific humidity, shortwave and longwave radiation, and the number of wet days (Huntingford et al., 2010). These emulated variables provide the necessary atmospheric forcing to drive LPJ-GUESS, creating a coupled system where land-atmosphere fluxes are areally integrated to update the atmospheric GHG concentration. By representing the atmospheric carbon balance as the net result of human-induced emissions, land-based sinks or sources, and a parameterised ocean sink, IMOGEN allows for a mechanistic study of climate feedbacks (Zelazowski et al., 2018). IMOGEN has previously been applied to investigations of regional uncertainties in methane mitigation options (Hayman et al., 2021) and the modulating impact of the nitrogen cycle on CO_2 fertilisation (Huntingford et al., 2022), demonstrating its capacity as a parsimonious yet physically grounded platform for multi-century coupled climate-land simulations.

Code and data availability

The specific version of the LandSyMM-IMOGEN coupled model framework code used in this study – LPJ-GUESS (revision trunk_r13078) with the embedded C++ implementation of IMOGEN, the Intermediary Controller, and the pre/post-processing and analysis scripts – is archived under the Mozilla Public License 2.0 at <https://doi.org/10.5281/zenodo.20600096>. The embedded IMOGEN is a C++ re-implementation of the standalone Fortran IMOGEN emulator (the pattern-scaling and energy-balance components, in the lineage of Huntingford et al. (2010); C. Huntingford's 2014 revision with the LPJ-GUESS coupling extensions of T. Pugh, 2015-2016), and is distinct from the JULES land-surface model within which IMOGEN also resides; the JULES code base is openly available (from JULES vn8.2) at <https://github.com/MetOffice/jules>, and the exact Fortran source together with its C++ re-implementation is included in the archived code above. The model-output datasets that reproduce the figures and tables – the integrated emissions and concentration trajectories, the climate-comparison statistics, Taylor-diagram



inputs and per-cell difference fields, the ecosystem-state statistics, full-period trajectories and carbon decomposition, and the CRU-JRA baseline climatology and MRI-ESM2-0 pattern/energy-balance drivers – are archived under the Creative Commons Attribution 4.0 International license at <https://doi.org/10.5281/zenodo.20600036>. The full raw model output (the regridDED climate library and the ecosystem-state runs) is regenerable from the archived code and is available from the authors on request.

1435 Third-party input datasets are cited in the relevant sections and are available from their providers (ISIMIP-3b, FAOSTAT, EDGAR, RCMIP, HILDA+, PLUM, CRU-JRA); the harmonised HILDA+/PLUM land-use and management products are available from the authors on request. PLUM v2, which generates the land-use and management projections used here, is a separately developed and maintained model described in Appendix B2 (Alexander et al., 2018; Engström et al., 2016); its source is available from the PLUM developers, and the harmonised products it produces for this study are regenerable from
 1440 the archived land-use-harmonisation code.

The input and reference datasets used in this study are openly available from their original providers: the ISIMIP-3b bias-corrected climate forcing (MRI-ESM2-0) from <https://www.isimip.org/>; the RCMIP (CMIP6) harmonised emissions from the Reduced Complexity Model Intercomparison Project (<https://www.rcmip.org/>) (Nicholls et al., 2021); the SSP socioeconomic drivers from the SSP database (<https://tntcat.iiasa.ac.at/SspDb/>); FAOSTAT agricultural activity and emissions data from
 1445 <https://www.fao.org/faostat/>; the EDGAR 2025-release emissions inventory from <https://edgar.jrc.ec.europa.eu/> (Crippa et al., 2025); the HILDA+ v2 land-use reconstruction from <https://doi.pangaea.de/10.1594/PANGAEA.974335> (Winkler et al., 2021); and the Global Lakes and Wetlands Database (GLWD, Level 3) from <https://www.hydrosheds.org/products/glwd> (Lehner and Döll, 2004). The observational evaluation references are the Global Methane Budget (Saunois et al., 2025), the Global Nitrous Oxide Budget (Tian et al., 2024), the Global Carbon Budget (Friedlingstein et al., 2025), and the atmospheric greenhouse-gas
 1450 concentration record compiled by the U.S. EPA (U.S. Environmental Protection Agency, 2024) from the NOAA Global Monitoring Laboratory and AGAGE instrumental series, extended with the Law Dome ice-core record (MacFarling Meure et al., 2006).

Author contributions

AA, MR, PA, PMA, SR designed the study and developed the concept for the LandSyMM framework and the IMOGEN
 1455 coupling. DB co-developed and implemented the LandSyMM coupling framework and methodology, including IPCC Tier-1 emissions modules, as well as IMOGEN refactoring and further development for integration into LPJ-GUESS. DB also configured and ran IMOGEN and LPJ-GUESS model simulations, and performed the vegetation dynamics analysis. TP provided guidance on operating the original Fortran IMOGEN engine, including preliminary test configurations with LPJ-GUESS, which informed the coupling implementation. GM provided the CMIP6 climate patterns and energy-balance-model parameters used
 1460 to drive the emulator. CH and GH developed the original IMOGEN framework on which the C++ re-implementation in this study is based. BA configured and ran the PLUM model simulations and provided corresponding land-use scenario data. SR provided the LUH2-based code to perform historic (HILDA+)-to-scenario (PLUM) land-use harmonisation. AA contributed to data analysis and validation. All authors contributed to manuscript revision and approved the final version.



Competing interests

1465 The authors declare that they have no competing interests.

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