Re-Livestock
RESILIENT FARMING SYSTEMS

D 6.1: Baseline for current and future circular livestock systems

Contents

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Executive Summary¡Error! Marcador no definido.

This deliverable links the Global-CiFoS food-system optimisation model with LPJmL5 to produce a 2020 baseline and 2050 RCP baselines (three General Circulation Models (GCMs)), including livestock systems under constant animal numbers and fixed human diets. The objective was to establish business-as-usual (RCP7) trajectories and quantify what can already be achieved (in terms of minimizing the environmental impact) by optimising circular biomass flows—reallocating feed toward processing by-products, substituting mineral fertilisers with recycled nutrients, and freeing land—without changing diets or herd/flock sizes. RCP2.6 baselines were developed as preparation for analyzing sustainable trajectories in Task 6.2.

Globally, BAU-2050 (for RCP2.6 and RCP7) raises environmental pressures relative to 2020 (GHG +16.8–18% to 6.60–6.67 Gt CO_2-eq yr^{-1}; land use +2.9–5% to 5.53–5.64 billion ha; nitrogen +35–40% to 409–423 Mt yr^{-1}; phosphorus +41–46% to 51.5–53.4 Mt yr^{-1}). Food system optimisation and adding circularity reverses most of these increases: GHG fall by 27.1% (to 4.12 Gt CO_2-eq), land use drops by 38.9% (to 3.28 billion ha), and nutrient use is substantially lower than BAU (nitrogen and phosphorus remain above 2020 by 22.8% and 19.3%, respectively). The BAU global animal total rises by about 35% versus 2020, driven by poultry and dairy; the circular gains above are achieved without altering those numbers.

In Europe, BAU-2050 already shows moderate declines relative to 2020 (GHG −16.7 to −22.9% to 0.44–0.41 Gt CO_2-eq; land −10.9 to −12.4% to 164–161 Mha; nitrogen −9.4% to roughly unchanged; phosphorus −4.8% to +8.6%), The lower projected environmental impacts can be largely attributed to the reduction in total animal numbers by about 22%. Optimised food system scenarios combined with circularity, amplify reductions markedly: GHG −51.9% (to 0.25 Gt CO_2-eq), land −37.7% (to 115 Mha), nitrogen −13.3%, and phosphorus −15.5 %. Results are robust across the three GCMs used for this study; inter-model variation (expressed as variation in plant production) is slight and does not alter the direction or magnitude of the main trends.

The principal levers to reduce environmental impacts of the food system while keeping animal production and diets at the projected baseline values, are: halving cropland N_2O via lower mineral-N inputs, legume expansion, and safe food waste used as fertilizer; freeing land — especially grassland — and reducing cropland for feed by shifting monogastric rations toward by-products and safely regulated food waste recycled streams; scaling circular fertilisers from manures, digestate/compost, and other sanitised sources; and tightening manure management (covered storage, low-emission application, anaerobic digestion with agronomic use of digestate).

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1. Introduction

Climate change poses a major challenge to global food systems, especially livestock production, which is vital for food security but accounts for about 15% of anthropogenic greenhouse gas emissions and 31% of food system emissions worldwide (Crippa et al., 2021). Rising temperatures, shifting precipitation patterns, and extreme weather events threaten feed availability, animal health, and productivity, while increasing demand for animal-sourced foods in 2050 aggravates environmental pressures (Rojas-Downing et al., 2017). With the global population projected to reach 9.7 billion by 2050, sustainable livestock systems will be essential for meeting nutritional needs while staying within planetary boundaries (UN, 2024). Circular food systems, which prioritize efficient biomass utilization and nutrient recycling, offer a promising framework to mitigate environmental impacts while ensuring food security (Simon et al., 2024; Van Zanten et al., 2023; Van Zanten et al., 2018).

Recent scientific advancements have developed sophisticated modeling approaches to understand these dynamics. Dynamic global vegetation models (DGVMs), such as the Lund-Potsdam-Jena managed Land (LPJmL, version 5) model, simulate the impacts of climate change on crop yields, water resources, and land use patterns, providing critical insights into agricultural productivity under varying climatic conditions (Heinke et al., 2023; Schaphoff et al., 2018). Concurrently, environmental optimization models like the Circular Food Systems (Global-CiFoS, v1.0) model explore redesigns of food systems to maximize nutritional output while minimizing environmental impacts, with a focus on the role of livestock in biomass utilization and nutrient cycling (Simon et al., 2025; Van Zanten et al., 2023). These models have been successful in assessing individual components of food systems or the food system under current conditions, yet their integration to evaluate the food systems crop and livestock sector redesigns under diverse future climate scenarios remains underexplored.

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This deliverable addresses this critical knowledge gap by establishing a linkage between the CiFoS and LPJmL models. By connecting these modelling frameworks, the study enables a comprehensive assessment of how climate change influences biomass availability and the potential for redesigning food livestock systems based on circularity holistically from a food system's perspective. Utilizing the latest climate data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) and the Coordinated Regional Climate Downscaling Experiment (CORDEX), this task 6.1 within the Re-Livestock EU-Project generates baseline scenarios for the current state of livestock production and projects future biomass availability under various Representative Concentration Pathways (RCPs). Specifically, RCP7, representing a business-as-usual (BAU) scenario, is employed across all baseline analyses for 2020 and 2050 to maintain consistency with BAU assumptions. Three distinct General Circulation Models (GCMs) are used to capture variability in climate impacts on primary production systems. We chose these models based on their ability to represent a range of potential climate futures. RCP2.6, representing a sustainable future scenario, is also considered to represent more sustainable food system trajectories baselines where consumption patterns in 2050 are becoming more healthy and crop production management becomes more sustainable. However, RCP2.6 trajectories are not the focus of this task and will be used in task 6.2 . The focus of task 6.1 is to establish a robust foundation for understanding business-as-usual trajectories for current and future food production systems. This work serves as a critical precursor to the subsequent task 6.2, where innovative livestock strategies together with dietary shifts based on the latest Eat-Lancet Commission's recommendations (EAT-Lancet 2.0 Diet), will be evaluated (Willett et al., 2019). By providing these baseline scenarios, this deliverable contributes to the development of resilient and sustainable food systems capable of addressing the multifaceted challenges posed by climate change.

2. Objectives

This task sets up the linkage between the CiFOS and LPJmL models and creates the data required to develop a base run for the current situation, as well as the available biomass for different representative concentration pathways based on the latest generation of global and regional climate models (CMIP6/CORDEX). It will explore ways of redesigning the livestock sector for each RCP given levels of biomass (creating RCP baselines) without accounting for specific mitigation or adaptation practices.

We will model the innovations and practices within Deliverable 6.2 of this project. Therefore, these tasks are not included in the deliverable 6.1. In task 6.2 we will then focus on the innovations.

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3. Methods

LPJmL: Crop Production for different climate scenarios and management practices

The LPJmL model simulated crop production under various climate scenarios and management practices. For this deliverable, we utilized the latest CMIP6 data to assess the impact of different RCPs on crop yields. The model was configured to run under RCP7, which represents a business-as-usual scenario without significant mitigation efforts and under RCP2.6, which represents the 'green path'.

Scenario assumptions for LPJmL model runs

The assumptions for the LPJmL model runs to generate crop and grass yields are shown in Table 1:

Table1. LPJmL model setup overview.

Category	Details
RCPs	RCP7.0 (business-as-usual) RCP2.6 (taking the green road)
Crop Types	Major rainfed and irrigated arable crops and grassland (see Table 4)
GCMs	GCM1: UKESM1-0-LL GCM3: MPI-ESM1-2-HR GCM5: GFDL-ESM4
Management Practices	Irrigation: Drip vs. conventional (IrriC) Fertilization: Balanced, manure-based Tillage: Conventional (Till) vs. no-tillage (No-Till)
Baseline Years	2020 2050
Output Variables	Harvested carbon in storage organ per crop (pft_harvestc)

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All scenarios' yield were modelled as water-limited. Drip irrigation was assumed to result in higher yields under conditions of water scarcity. This behaviour was based on the premise that more efficient water delivery systems can reduce drought stress during critical crop growth periods. Accordingly, yield improvements linked to drip irrigation were only applied in regions identified as experiencing water shortages(Guan et al., 2025; Yang et al., 2023). Similarly, no-tillage (NT) systems were assumed to increase yields in arid climates, reflecting their capacity to conserve soil moisture and reduce water losses from evapotranspiration (Hashimi et al., 2023; Modiba et al., 2024). The fertilization was assumed to be balanced and and no nitrogen limitations were assumed. This was done to match the balanced fertilization approach used in the CiFoS model.

We selected the three GCM models so they cover the most pessimistic (GCM1: UKESM1-0-LL)(Sellar et al., 2019), intermediate (GCM3: MPI-ESM1-2-HR)(Müller et al., 2018) and optimistic (GCM5: GFDL-ESM4)(Dunne et al., 2020) response of the harvested carbon variable (pft_harvestc) over time. The difference between the GCMs resulted from differences in assumptions regarding radiative force, temperature, and precipitation patterns.

One big difference between the two RCP2.6 and RCP7 was the CO2 fertilization. RCP7 was assumed to have a much higher CO2 fertilization compared to RCP2.6 which led to higher yields in carbon in the RCP7 scenario. This was based on the assumption that RCP7 represents a business-as-usual scenario with high CO2 emissions, while RCP2.6 represents a more sustainable future with lower CO2 emissions (Fricko et al., 2017; van Vuuren et al., 2017).

All the model assumptions of the LPJmL model configuration used for this deliverable are described in greater detail in milestone 28 (MS28 of WP6) (Rolinski, 2025).

Final scenario design of nine LPJmL scenarios

Based on the options shown in Table 1, a final combination of scenario assumptions was formulated and generated using the LPJmL model. The final assumptions and modelled scenarios are shown in Table 2.

Table 2: Scenario assumptions for LPJmL model runs.

SSP	GCM	RCP	Year	Tillage	Irrigation	Organic Fertilizer
SSP2	1	7	2020	Till	IrriC	Manure
SSP2	3	7	2020	Till	IrriC	Manure
SSP2	5	7	2020	Till	IrriC	Manure
SSP1	1	2.6	2050	No-Till	Drip	Manure
SSP1	3	2.6	2050	No-Till	Drip	Manure
SSP1	5	2.6	2050	No-Till	Drip	Manure
SSP2	1	7	2050	Till	IrriC	Manure
SSP2	3	7	2050	Till	IrriC	Manure
SSP2	5	7	2050	Till	IrriC	Manure

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The socio-economic pathways (SSPs) are linked to the RCPs to further contextualize these assumptions and add a social dimension. SSP1 ("Sustainability – Taking the Green Road") envisions a future with strong environmental stewardship, low inequality, and accelerated adoption of resource-efficient technologies (van Vuuren et al., 2017). In contrast, SSP2 ("Middle of the Road") represents a continuation of historical trends, with only gradual progress toward sustainability and moderate mitigation and adaptation challenges (Fricko et al., 2017).

LPJmL output description

The LPJmL model was run with the above assumptions to generate crop production data for the year 2020 and 2050 under different RCPs and GCMs. The model output includes harvested carbon per crop type, which was then converted to dry matter yields using the conversion factor of 0.45 (Ma et al., 2018). The results were aggregated from pixels to the region-climate-soil zones used in the CiFoS model (W. Simon et al., 2025; Van Zanten et al., 2023).

Crop Production (LpjmL) for different climate scenarios and management practices

The output of the LPJmL model simulations were used to estimate the harvested carbon per crop type for the years 2020 and 2050 under different RCPs and GCMs. Harvested carbon (netcdf band: pft_harvestc) was simulated per pixel for the crops in Table 3.

Table 3. LPJmL crop types used to map the LPJmL crops to the CiFoS model crops.

LPJmL Crop
rainfed temperate cereals
rainfed rice
rainfed maize
rainfed tropical cereals
rainfed pulses
rainfed temperate roots
rainfed tropical roots
rainfed oil crops sunflower
rainfed oil crops soybean
rainfed oil crops groundnut
rainfed oil crops rapeseed
rainfed sugarcane
rainfed others
rainfed grassland
---
irrigated temperate cereals
irrigated rice
irrigated maize
irrigated tropical cereals
irrigated pulses
irrigated temperate roots
irrigated tropical roots
irrigated oil crops sunflower
irrigated oil crops soybean
irrigated oil crops groundnut

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irrigated oil crops rapeseed
irrigated sugarcane
irrigated others
irrigated grassland

Now the LPJmL crops were mapped to the 45 CiFoS crops and the harvested carbon (pft_harvestc) was converted to dry matter yields using Equation 1:

$$\text{Yield}_{\text{tDM/ha}} = \frac{\text{Harvested Carbon}_{\text{gC/m}^2}}{0.45} \times 0.01 \qquad (1)$$

Where:

- Yield_{tDM/ha}: Yield in tonnes of dry matter per hectare (tDM/ha)
- Harvested Carbon_{gC/m²}: Harvested carbon in grams of carbon per square meter (gC/m²)
- 0.45 is the fraction of carbon in dry matter (45.01%), based on Ma et al. (2018)
    - converts from g/m² to t/ha

The yields were then aggregated from pixels to region-climate-soil zones used in CiFoS where crop variables are assumed to behave homogenously regarding productivity (Batjes, 2009; Fischer et al., 2021; W. Simon et al., 2025).

Filtering approach for meaningful agronomic yield estimates

To ensure that only agronomically meaningful yield values were included in the analysis, we applied a two-step filtering procedure to the crop yield raster data. First, all pixel values below 50 gC/m² were set to NA, effectively excluding non-cropland and extremely low-yielding areas that are unlikely to represent productive agriculture. Second, for each crop (raster band), the lowest 35% of remaining yield values were removed by calculating the 35th percentile and setting all values below this threshold to NA. The percentile cutoff value was chosen so the resulting yields would match expected crop productivity statistics. This approach reduces the influence of outliers and non-representative low yields, resulting in more robust estimates of mean yield per crop.

Defining the current (year 2020) harvested crop and grassland area

For the harvested arable land we used the MapSPAM dataset 'Global Spatially-Disaggregated Crop Production Statistics Data for 2020 Version 1.0', which provides spatially explicit data on harvested crop land area (IFPRI, 2024). For grassland area, we used the HYDE dataset, which provides grassland area for pasture and rangeland land types (Klein Goldewijk et al., 2017). As with the yields we aggregate the harvested area from pixels to the region-climate-soil zones (Batjes, 2009; Fischer et al., 2021).

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Future land use projections for 2050

To represent the future land changes in 2050, we used the Magpie model output land change factors (Dietrich et al., 2025). The Magpie model provides factors of land increase or decrease for the year 2050 [1=no change in land; <1= reduction in land area; >1= increase in land area]. The 2050 area factors projections were then mapped to the CiFoS region-climate-soil zones. In this way, we obtained the yield and harvested area for each crop type in each region-climate-soil zone per different GCMs and RCPs. In total we used 9 different crop datasets related to the scenarios described in Table 2.

Circular Food System (CiFoS) model

Livestock Production used for the CiFoS model

Baseline animal number data comes from GLEAM 3.0 for the reference year 2015 (FAO, 2022). These numbers served as the basis for estimating current animal populations. Animal production systems (APS) include beef (CTL_B) and dairy cattle (CTL_D), buffalo beef (BFL_B), buffalo dairy (BFL_D), sheep (SHE), goats (GOT), pigs (PIG), and poultry (CHK). Aquaculture was defined as Carps, Catfishes, Salmonids, Shrimps, and Tilapias. The linked production levels (APSLevels) are defined in Table 4:

Table 4: Animal Production Systems (APS) and their production types (APSLevels). Green shading indicates the animals that we show in the results.

APS	APSLevel
BFL_B	Grassland
BFL_B	Mixed
BFL_D	Grassland
BFL_D	Mixed
Carps	Aquaculture
Catfishes	Aquaculture
CHK	Broiler
CHK	Layer
CHK	Backyard
CTL_B	Grassland
CTL_B	Mixed
CTL_D	Grassland
CTL_D	Mixed
GOT_B	Grassland
GOT_B	Mixed
GOT_D	Grassland
GOT_D	Mixed
PIG	Backyard
PIG	Industrial
PIG	Intermediate
Salmonids	Aquaculture
SHE_B	Grassland
SHE_B	Mixed
SHE_D	Grassland
SHE_D	Mixed
Shrimps	Aquaculture
Tilapias	Aquaculture

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Animal production factors for 2050

To estimate future change in country-level animal numbers for 2050, we combined baseline animal inventory data from GLEAM 3.0 (FAO, 2022) with scenario-based projections of food demand and productivity from the IMPACT and MAGPIE models (Dietrich et al., 2025; Rosegrant et al., 2012). The data was used to characterise the 2050 animal system including productivity trends:

- **Climate change impacts on livestock production** from heat stress were derived from Thornton et al. (2022). Thornton et al. (2022) provided only milk and meat. We then mapped the projection values to all the animal-sourced products based on our best of knowledge, as was done in the EAT-Lancet paper (Zanten et al., *submitted*).
- **Animal yield productivity trends** were taken from the IMPACT model (Rosegrant et al., 2012). The IMPACT model provided the yield productivitiy factor for 2050 for the different APS(Rosegrant et al., 2012).
- **Per capita food supply and protein supply projections** were derived from the MAGPIE model output for 2050 and represent future dietary trends (Dietrich et al., 2025).

Estimating Baseline Animal Numbers for 2050

However, from this we further needed to calculate the animal numbers in 2050. We used the following approach:

Mapping the food groups with APS systems: To be able to correct for the dietary change when estimating future changes in animal numbers, we mapped the CiFoS animal production systems to the food groups as follows (Table 5):

Table 5: Food group to Animal Production System (APS) mapping

Food Group	Mapped APS Codes
Dairy	BFL_D, CTL_D, SHE_D, GOT_D
Chicken	CHK
Eggs	CHK (same APS as chicken assumed)
Fish	Carps, Salmonids, Shrimps, Tilapias, Catfishes
Red Meat	PIG, BFL_B, CTL_B, SHE_B, GOT_B

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Deriving a population factor for 2050 compared to 2020: To correct for population changes between 2020 and 2050 we used current and projected population numbers for 2050 from Kc & Lutz (2017) to calculate a population factor. The population factor from 2020 to 2050 was derived as described by Equation 2:

$$\text{Population Factor} = \frac{\text{Population}_{2050}}{\text{Population}_{2020}} \qquad (2)$$

Where:

- Population Factor: Relative change of population of 2050 compared to 2020
- Population 2020: Number of people in 2020
- Population 2050: Number of people in 2050

Calculating the animal number factor for 2050 corrected for yield trends, population trends and dietary trends: With all the correction factors in place, the animal number factor for 2050 could then be computed using Equation 3:

$$\text{Animal Number Factor 2050} = \frac{\text{Food Supply Factor 2050} \times \text{Population Factor 2050}}{\text{Animal Yield Trend 2050}} \qquad (3)$$

Where:

- Animal Number Factor 2050: Relative change of animal numbers in 2050 compared to 2020
- Food Supply Factor 2050: Relative change of food supply in 2050 compared to 2020, derived from the MAGPIE model output (Dietrich et al., 2025).
- Population Factor 2050: Relative change of population in 2050 compared to 2020, derived from population projections (Kc & Lutz, 2017).
- Animal Yield Trend 2050: Relative change of animal yield in 2050 compared to 2020, derived from the IMPACT model output (Rosegrant et al., 2012).

Note: For APS or regions lacking yield data, a conservative fallback of no change (factor = 1) was applied.

Scaling the baseline animal numbers to 2050

Final 2050 animal numbers were calculated by multiplying baseline values by the derived animal number 2050 scaling factors. The resulting animal numbers reflects combined effects of dietary shifts, population growth, and productivity improvements on animal populations per country and species group.

Crop Production used for the CiFoS model

The crop production data for the CiFoS model is based on agronomically validated MAPSPAM 2020 (IFPRI, 2024). To capture variability between climate projections, we applied crop- and climate–soil zone–specific factors from LPJML simulations (three GCMs, provided by PIK in this project) to the MAPSPAM production data. The resulting harvested area and yield estimates were aggregated to the region–climate–soil zones used in CiFoS. This dataset was then used to estimate the available biomass for livestock production systems and human consumption.

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Scenario Descriptions in the CiFoS model

Base_2020

- The scenario represents the 2020 baseline regarding animal production and diets.
- Protein supply is fixed to statistical FAOSTAT 2020 values with +/- 5% slack.
- Crop areas are fixed to the 2020 statistical data (crops may expand within slack limits to make the model feasible, see footnote [1]).
- Fertilizer use is fixed at 2020 levels based on IFASTAT.

Objective: One-step minimization:

- Minimize deviation from 2020 primary production - Minimize deviation from 2020 food supply at the product level
- Minimize trade volumes to avoid unnecessary trade (soft constraint).

BAU_2050_RCP26 and BAU_2050_RCP7

- 2050 business-as-usual projection under RCP2.6 and 7.0.
- Animal numbers fixed to 2050 levels: these numbers are based on the Base_2020 run outputs and then combined with the animal number factors explained above
- Crop areas fixed but allowed to expand following MAgPIE area growth (with slack)
- Protein Food Supply fixed to future dietary projections with 20% slack
- Fertilizer fixed and increased by 41% globally compared to the Base_2020 scenario
- Feed composition can be optimized

Main differences between RCP2.6 and RCP7.0:
RCP2.6 assumes lower CO2 fertilization and more sustainable practices, while RCP7.0 assumes higher CO2 fertilization and business-as-usual practices. CO2 fertilization increases yields. All factors regarding future area and yield, animal numbers, and dietary projections differ for the RCPs.

Objective: One-step minimization:

- Minimize deviation from 2020 primary production - Minimize deviation from 2020 food supply at the product level
- Minimize trade volumes to avoid unnecessary trade (soft constraint).

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OptCir_2050

- Optimized 2050 diet and production system (BAU dietary targets are fixed).
  - Crop land area constraints relaxed
- Feed composition can be optimized
- Animal numbers fixed to 2050 levels.
- Minimize the difference between the modelled diets and the projected food supply provided by the MAGPIE model for 2050 (with slack)
- Fix the food supply outcome from the first run and minimize greenhouse gas emissions
- Maximum use of circular feed sources (e.g., by-products, food waste)
  - Enhanced nutrient recycling

Objective: Two-step minimization:

1. Minimize the difference between the modelled diets and the projected food supply provided by the MAGPIE model for 2050 (with slack)
2. Fix the food supply outcome from the first run and minimize greenhouse gas emissions

Uncertainty analysis

We calculated standard deviations across the climate models (three GCMs) to capture variability in projections. These values are reported alongside mean estimates or shown as error bars in the figures.

Modelling Environment and Data Analysis

The LPJmL model was run by Susanne Rolinski from PIK using their HPC cluster. All the model assumptions of the LPJmL model configuration used for this deliverable are described in greater detail in milestone 28 (MS28 of WP6) (Rolinski, 2025). All writing and analysis were done using Quarto with R (Posit Software, PBC, 2022; Team, 2024). All CiFoS modelling was performed in the General Algebraic Modelling Software (GAMS, version 49.0) (GAMS, 2024) using the Global CiFoS model (Global-CiFoS, v1.0), which is documented in detail by W. Simon et al. (2025). The CiFoS model was run on an HPC at Wageningen University & Research.

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4. Results and Discussion

Global and European crop and grassland production under different RCPs and GCMs

Global cropland production

In this section, we present the results of the crop and grassland production simulations under different climate scenarios and management practices using the LPJmL model output. The focus is on the baseline scenarios for 2020 and 2050 (RCP 2.6 and RCP 7), with a particular emphasis on the impact of climate change on crop and grassland harvested area, production, and yields.

Globally, the baseline (Base_2020) has the lowest harvested cropland area (1478.3 Mha), production (11.496 Bt), and yield (7,776.82 kg/ha). Both 2050 scenarios project an increased crop area (about 1655.7 Mha), and much higher production and yields. RCP7_2050 shows the highest production (21.833 Bt) and yield (13,186.14 kg/ha), indicating substantial intensification or productivity gains under this scenario. The standard deviations reflect the variability across different climate models, with future scenarios showing greater uncertainty, especially in production and yield (Table 6).

Table 6: Summary statistics of global crop production metrics by scenario with GCM variation. The GCM variation is shown as mean ± standard deviation. Abbreviations: Mha = Million hectares, Bt = Billion tonnes, kg/ha = Kilograms per hectare.

Scenario	Area (Mha)	Production (Bt)	Yield (kg/ha)
Base_2020	1478.3 ± 0.0	11.496 ± 0.036	7776.82 ± 24.65
RCP26_2050	1655.7 ± 0.0	18.259 ± 0.490	11027.48 ± 295.65
RCP7_2050	1655.7 ± 0.0	21.833 ± 0.547	13186.14 ± 330.45

European cropland production

In Europe, the baseline (Base_2020) also has the lowest harvested area (95.1 Mha), production (0.932 Bt), and yield (9,806.73 kg/ha). Both 2050 scenarios (RCP 2.6 and RCP 7) project a slightly increased crop area (99.3 Mha), and higher production and yields. RCP7_2050 shows the highest production (1.558 Bt) and yield (15,697.08 kg/ha), indicating greater intensification or productivity gains under this scenario. The standard deviations reflect the variability across different climate models, and show that there is greater uncertainty in yields in Europe compared to global trends (Table 7 and compared with Table 6).

Table 7: Summary statistics of European crop production metrics by scenario with GCM variation. The GCM variation is shown as mean ± standard deviation. Abbreviations: Mha = Million hectares, Bt = Billion tonnes, kg/ha = Kilograms per hectare.

Scenario	Area (Mha)	Production (Bt)	Yield (kg/ha)
Base_2020	95.1 ± 0.0	0.932 ± 0.006	9806.73 ± 65.11
RCP26_2050	99.3 ± 0.0	1.333 ± 0.046	13426.12 ± 460.23
RCP7_2050	99.3 ± 0.0	1.558 ± 0.060	15697.08 ± 607.18

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Global grassland production

In this section, we summarize the grassland areas, production, and yields under different climate scenarios. Grassland areas include pasture, rangeland, and arable grass crops. The analysis is conducted for both global and European grassland areas.

All scenarios show the same grassland area (3269.0 Mha) because the area increase is assumed in 2050. The Base_2020 scenario shows the lowest grassland production of 26.481 Bt and an average yield of 8,100.73 kg/ha. Both 2050 scenarios (RCP26 and RCP7) project higher production and yields compared to Base_2020. RCP7_2050 shows a production of 29.665 Bt and a yield of 9,074.51 kg/ha, indicating significant grassland productivity gains under this scenario. The standard deviations reflect the variability across different climate models. Other than for the cropland, grassland seems to be more resilient to climate change impacts (Table 8).

Table 8: Summary statistics of grassland areas, production, and yields by scenario with GCM variation. The GCM variation is shown as mean ± standard deviation. Abbreviations: Mha = Million hectares, Bt = Billion tonnes, kg/ha = Kilograms per hectare.

Scenario	Area (Mha)	Production (Bt)	Yield (kg/ha)
Base_2020	3269.0 ± 0.0	26.481 ± 0.088	8100.73 ± 26.98
RCP26_2050	3269.0 ± 0.0	29.610 ± 0.064	9057.96 ± 19.51
RCP7_2050	3269.0 ± 0.0	29.665 ± 0.007	9074.51 ± 2.22

European grassland production

The European grassland areas show similar trends. All scenarios show a harvested grassland area of 85.4 Mha. The Base_2020 demonstrates with 1.159 Bt and a yield of 13,564.95 kg/ha the lowest production and yield. Both 2050 scenarios (RCP 2.6 and RCP 7) project higher production and yields. RCP7_2050 shows a production of 1.449 Bt and a yield of 16,963.42 kg/ha, indicating significant productivity gains under this scenario. The data also show that in Europe the climate change impacts lead to much higher yield variation (e.g., RCP7_2050: ± 41.11 kg/ha) compared to the global trends (e.g., RCP7_2050: ± 2.22 kg/ha) (Table 9).

Table 9: Summary statistics of European grassland areas, production, and yields by scenario with GCM variation. The GCM variation is shown as mean ± standard deviation. Abbreviations: Mha = Million hectares, Bt = Billion tonnes, kg/ha = Kilograms per hectare.

Scenario	Area (Mha)	Production (Bt)	Yield (kg/ha)
Base_2020	85.4 ± 0.0	1.159 ± 0.002	13564.95 ± 18.32
RCP26_2050	85.4 ± 0.0	1.450 ± 0.005	16976.30 ± 54.85
RCP7_2050	85.4 ± 0.0	1.449 ± 0.004	16963.42 ± 41.11

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Food system outcomes for animal production baseline scenarios using the CiFoS model

In this deliverable 6.1, we focus primarily on the crop and animal production systems and dietary baseline scenarios for the year 2020 and two different future scenarios for the year 2050 for RCP 2.6 and 7. We also added an optimized scenario where we fixed the animal production to baseline numbers and also to current diets, but released the current land constraints and optimized for reduced emissions. These are not strict baseline scenarios in all food system areas, but give an indication of the potential to reduce environmental impacts by optimizing the cropping systems, animal feed, waste handling, while keeping animal production and diets at current levels. In the next task 6.2, we will then explore the full potential to reduce the environmental impact by optimizing also the animal production systems and diets.

Baseline animal numbers for 2020 and 2050

Global

Total livestock numbers (i.e., beef cattle, dairy cattle, chicken, pigs) increase from 21,251 million head in 2020 to 28,736 million in 2050 (+35.2%; Figure 1). Growth is led by chickens, which rise from 19,252 million to 26,578 million (+38.1%). Within poultry, Backyard chickens go from 2,481 to 4,344 million (+75%), Layers from 5,998 to 9,720 million (+62%), and Broilers from 10,773 to 12,514 million (+16%). Dairy cattle expand from 607 to 891 million (+46.7%), with both Grassland (+51.1%) and Mixed (+45.1%) systems increasing. Beef cattle grow from 545 to 601 million (+10.3%; Grassland +14.9%, Mixed +8.3%). In contrast, pigs decline from 847 to 666 million (–21.4%), driven by reductions in Industrial (–31.0%), Intermediate (–19.0%), and slight decreases in Backyard (–2.0%). Overall, the 2050 global herd is substantially larger and increasingly dominated by poultry and dairy.

Europe

Total animal numbers fall from 2,143 million head in 2020 to 1,666 million in 2050 (–22.3%; Figure 1). Chickens decrease from 1,899 to 1,492 million (–21.4%), with notable drops in Backyard chickens (–36.9%) and Broilers (–31.9%), while Layers increase slightly (+1.7%). Dairy cattle decline from 91.0 to 62.1 million (–31.7%) and beef cattle from 28.6 to 24.0 million (–16.0%), with decreases across Grassland and Mixed systems. Pigs fall from 124.9 to 87.0 million (–30.4%), including Industrial (–30.3%), Intermediate (–31.4%), and Backyard (–26.7%) categories. In sum, European livestock numbers contract across all major groups by 2050, in clear contrast to the global expansion.

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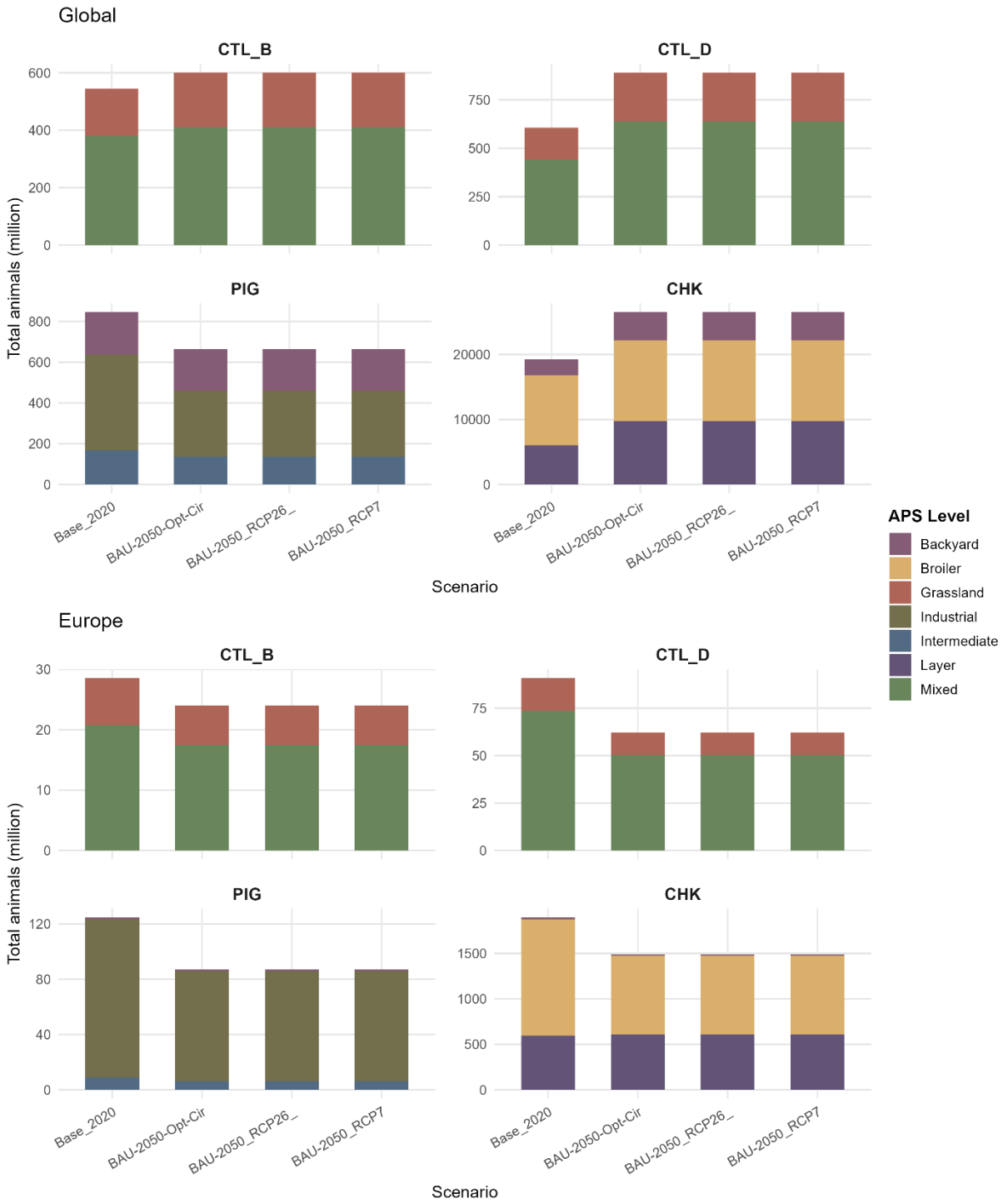

Figure 1. Global and European livestock numbers by scenario and animal production systems (APS) and levels. Panels show CTL_B (beef cattle), CTL_D (dairy cattle), PIG (pigs), and CHK (chickens). Top row = Global; bottom row = Europe. Stacked bars indicate the mix of production system levels (colors) under Base_2020 and BAU-2050 variants (3 GCMs). Units: million head. Food product—primary or processed foods otherwise edible for humans that are used directly as feed (e.g., grains/flours, vegetable oils, sugar, milk/meat products). Processing by-product—co-products and residues from crop processing, including both human-edible and non-edible streams (e.g., bran and hulls, oilseed cakes, molasses/whey). Forage product—dedicated fodder crops grown for feed

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only (e.g., alfalfa/clover, forage cereals, maize silage, fodder roots). Grass product—pasture and sown grass used as fresh, hay, or silage from arable fields, pastures, or rangelands. Waste—post-harvest or consumption food-waste streams diverted to feed (where present).

Environmental Impacts

Global

The global environmental impacts of the different scenarios compared to the 2020 baseline are summarized in Table 10. In the baseline (Base_2020), greenhouse gas (GHG) emissions amount to 5.65 Gt CO_2-eq, land use to 5,369[1] Mha, nitrogen use to 303 Mt, and phosphorus use to 36.6 Mt.

Under the BAU_2050 scenarios, environmental pressures increase across most categories. GHG emissions rise to 6.67 Gt CO_2-eq in BAU_2050_RCP26 and 6.60 Gt CO_2-eq in BAU_2050_RCP7, corresponding to increases of +18% and +16.8% relative to the baseline. Land use also expands (based on land expansion values we used), reaching 5,526[1] Mha (+2.9%) in BAU_2050_RCP26 and 5,636[1] Mha (+5%) in BAU_2050_RCP7. Nutrient pressures grow more strongly: nitrogen use increases to 409 Mt (+35.1%) and 423 Mt (+39.7%) in BAU_2050_RCP26 and BAU_2050_RCP7, respectively, while phosphorus use rises to 51.5 Mt (+40.8%) and 53.4 Mt (+45.8%).

By contrast, the circular optimization scenario for 2050 reduces environmental impacts compared to Base_2020 considerably. GHG emissions falling to 4.12 Gt CO_2-eq (–27.1%) and land use to 3,281 Mha (–38.9%). Nitrogen use decreases to 372 Mt (+22.8% relative to baseline, but considerably lower than BAU), while phosphorus use reaches 43.7 Mt (+19.3%). It is important to note here that land use, nitrogen, and phosphorus use were not minimized as single objectives (see the scenario descriptions in the methods). Doing so could likely lead to lower impacts in the minimized environmental impact category.

Overall, the BAU_2050 scenarios suggest substantial increases in nutrient pressures and moderate increases in land use and emissions, whereas the optimized circular pathway substantially reduces land use and GHG emissions while partly mitigating nutrient demand (Table 10).

[1] It is important to note that land use in our baseline scenarios is higher than in other comparable studies. Global land use in 2020 is generally estimated at about 4,800 Mha, with projections suggesting a ~4% increase by 2050 (~4,992 Mha). The higher values in our model result from several strict constraints: fixing animal production and current diets, requiring a set share of grass in ruminant diets, and excluding certain feed sources such as crop residues (about one quarter of global feed biomass), roadside grazing, and others. Most of the additional land use, therefore, occurs in grasslands to compensate for the missing roughage in our modelling approach. Because of these constraints, and given uncertainties in global grassland use and animal numbers, cropland could not be fixed precisely at expected values. We therefore allowed the model some flexibility to ensure feasibility. We will address this model behavior in task 6.2 further to better match actual land use numbers.

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Table 10. Global results for greenhouse gas (GHG) emissions, land use, nitrogen use, and phosphorus use across scenario groups. Values represent the mean ± standard deviation across general circulation models (GCMs). Relative changes (%) are shown compared with the 2020 baseline (Base_2020). Scenario groups include Base_2020, baseline projections for 2050 under climate pathways RCP2.6 and RCP7.0 (BAU_2050_RCP26, BAU_2050_RCP7), and the optimized scenario (OptCir_2050). Units: GHG emissions in gigatonnes CO_2-equivalent per year (Gt CO_2-eq yr^{-1}), land use in million hectares (Mha), nitrogen in teragrams per year (Tg N yr^{-1}), and phosphorus in teragrams per year (Tg P yr^{-1}).

Category	scenario	Mean ± SD	Boundary	Base_2020
GHG emissions	Base_2020	5.65 ± 0	5	0%
GHG emissions	BAU_2050_RCP26	6.67 ± 0.04	5	18%
GHG emissions	BAU_2050_RCP7	6.6 ± 0.04	5	16.8%
GHG emissions	OptCir_2050	4.12 ± 0.02	5	-27.1%
Land use	Base_2020	5368.51 ± 0	3600	0%
Land use	BAU_2050_RCP26	5526.4 ± 338.79	3600	2.9%
Land use	BAU_2050_RCP7	5636.4 ± 20.42	3600	5%
Land use	OptCir_2050	3281.02 ± 118.6	3600	-38.9%
Nitrogen	Base_2020	302.82 ± 0	134	0%
Nitrogen	BAU_2050_RCP26	409.19 ± 4.34	134	35.1%
Nitrogen	BAU_2050_RCP7	423.02 ± 5.05	134	39.7%
Nitrogen	OptCir_2050	371.84 ± 2.25	134	22.8%
Phosphorus	Base_2020	36.6 ± 0	16	0%
Phosphorus	BAU_2050_RCP26	51.52 ± 0.45	16	40.8%
Phosphorus	BAU_2050_RCP7	53.37 ± 0.63	16	45.8%
Phosphorus	OptCir_2050	43.69 ± 1.37	16	19.3%

Europe

The environmental impacts of the different scenarios for Europe compared to the 2020 baseline are presented in Table 11. In the baseline (Base_2020), greenhouse gas (GHG) emissions amount to 0.53 Gt CO_2-eq, land use to 184 Mha, nitrogen use to 29.9 Mt, and phosphorus use to 2.94 Mt.

Under the BAU_2050 scenarios, most environmental indicators show modest reductions compared to the baseline. GHG emissions fall to 0.41 Gt CO_2-eq in BAU_2050_RCP26 (–22.9%) and 0.44 Gt CO_2-eq in BAU_2050_RCP7 (–16.7%). Land use decreases to 164 Mha (–10.9%) and 161 Mha (–12.4%) in BAU_2050_RCP26 and BAU_2050_RCP7, respectively. Nitrogen use shows a smaller change, declining to 27.1 Mt (–9.4%) under RCP26 and remaining near baseline levels at 30.0 Mt (+0.3%) under RCP7. Phosphorus use also changes little, reaching 2.80 Mt (–4.8%) in BAU_2050_RCP26 and 3.19 Mt (+8.6%) in BAU_2050_RCP7.

The optimization scenarios achieve more substantial reductions. The OptCir_2050 scenario produces similarly strong improvements, with GHG emissions of 0.25 Gt CO_2-eq (–51.9%)

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and land use of 115 Mha (–37.7%). Nutrient use is reduced compared to the baseline, with nitrogen at 25.9 Mt (–13.3%) and phosphorus at 2.49 Mt (–15.5%).

Overall, while BAU_2050 scenarios suggest moderate environmental efficiency gains for Europe, particularly for GHG emissions and land use due to decreased numbers of animals, the optimized pathways deliver much larger reductions across all environmental indicators, especially in GHG emissions, land use, and phosphorus use.

Table 11. European results for greenhouse gas (GHG) emissions, land use, nitrogen use, and phosphorus use across scenario groups. Values represent the mean ± standard deviation across general circulation models (GCMs). Relative changes (%) are shown compared with the 2020 baseline (Base_2020). Scenario groups include Base_2020, baseline projections for 2050 under climate pathways RCP2.6 and RCP7.0 (BAU_2050_RCP26, BAU_2050_RCP7), and the optimized scenario (OptCir_2050). Units: GHG emissions in gigatonnes CO_2-equivalent per year (Gt CO_2-eq yr^{-1}), land use in million hectares (Mha), nitrogen in teragrams per year (Tg N yr^{-1}), and phosphorus in teragrams per year (Tg P yr^{-1}).

Category	scenario	Mean ± SD	Base_2020
GHG emissions	Base_2020	0.53 ± 0	0%
GHG emissions	BAU_2050_RCP26	0.41 ± 0	-22.9%
GHG emissions	BAU_2050_RCP7	0.44 ± 0.01	-16.7%
GHG emissions	OptCir_2050	0.25 ± 0	-51.9%
Land use	Base_2020	184.23 ± 0	0%
Land use	BAU_2050_RCP26	164.2 ± 0.37	-10.9%
Land use	BAU_2050_RCP7	161.43 ± 1.73	-12.4%
Land use	OptCir_2050	114.83 ± 8.74	-37.7%
Nitrogen	Base_2020	29.91 ± 0	0%
Nitrogen	BAU_2050_RCP26	27.09 ± 0.04	-9.4%
Nitrogen	BAU_2050_RCP7	30 ± 0.5	0.3%
Nitrogen	OptCir_2050	25.92 ± 2.18	-13.3%
Phosphorus	Base_2020	2.94 ± 0	0%
Phosphorus	BAU_2050_RCP26	2.8 ± 0.01	-4.8%
Phosphorus	BAU_2050_RCP7	3.19 ± 0.04	8.6%
Phosphorus	OptCir_2050	2.49 ± 0.24	-15.5%

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Exploring strategies and levers for redesigning the food system to reduce environmental impacts at constant animal numbers and human diets

The analysis below synthesises the main levers emerging from our scenario. Unless stated otherwise, numbers refer to the global system; where European patterns diverge, we highlight them explicitly.

Reducing greenhouse gas emissions

Across scenarios, cropland processes account for roughly half of total GHG emissions (Figure 2). Under circular optimisation, total GHGs fall by 27% globally (from 5.65 to 4.12 Gt CO_2-eq yr^{-1}) and by 52% in Europe (from 0.53 to 0.25 Gt CO_2-eq yr^{-1}) because cropland emissions drop sharply. The largest driver is a halving of direct N_2O emissions from N application in the optimised runs, which is modelled as a function of fertilizer type and climatic conditions (Figure 2). Dry conditions reduce the direct emissions, while the biggest factor to reduce direct N2O emissions is the reduction of synthetic fertilizer. N volatilisation declines only modestly which is influenced by the climatic conditions. A global-only lever is the substantial decline in rice methane when land is freed (i.e., in OptCir), which is minor in Europe.

Strategies to reduce food system emissions at BAU diets and animal numbers (EU-relevant)

- **Cut synthetic N inputs** through: (i) legume area expansion; (ii) use of circular/organic fertilizers (e.g., food waste).
- **Scale circular N fertilizers**: compost from food waste and manures, with end-of-waste standards to ensure quality and farmer uptake.
- **Reducing trade by increasing circularity:** Circularity helps to reduce transportation emissions (→ marginal).
- **Global engagement**: support rice methane emission reduction strategy as a non-EU mitigation effort with substantial global returns.

Animal emissions remain comparatively stable across scenarios (Figure 2); given constant animal numbers, the source of the slight emission reduction comes from circular feedstuffs like by-products and treated food waste, and land levers rather than herd structure.

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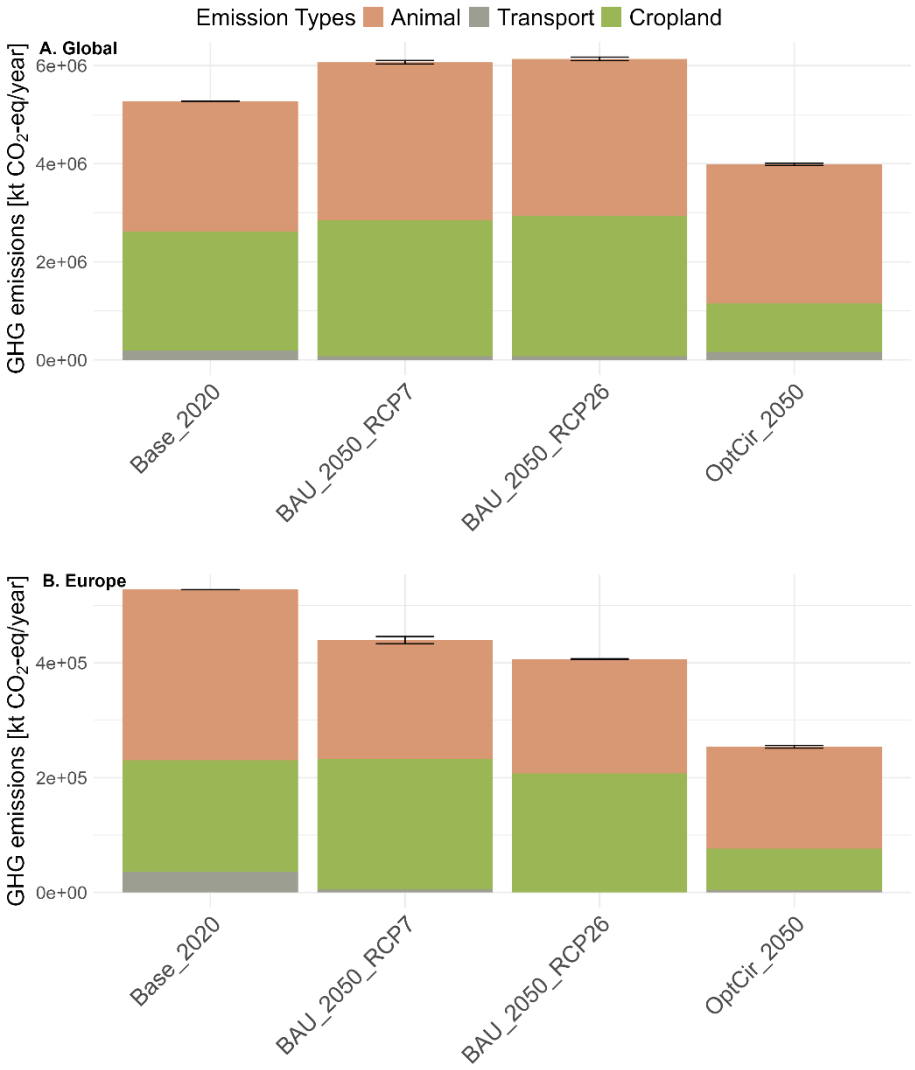

Figure 2. Greenhouse gas (GHG) emissions by source for (top) Global and (bottom) Europe across scenario groups. Bars represent the mean emissions across general circulation models (GCMs), stacked by emission type (Animal, Transport, Cropland). Black error bars indicate the standard deviation across GCMs for the total emissions per scenario group. Scenario groups include the 2020 baseline (Base_2020), baseline projections for 2050 under climate pathways RCP7.0 and RCP2.6 (BAU_2050_RCP7, BAU_2050_RCP26), and the optimized circular scenario (OptCir_2050). Emissions are expressed in kilotons of carbon dioxide equivalents per year (kt CO_2-eq yr^{-1}).

Reducing land use

Optimised scenarios reduce global land use by ~39% (from ~5.37 to 3.36 billion ha) and European land use by 38%, primarily via freeing grassland from production. The grassland reduction trend is global and strong; Europe shows a similar pattern. At the same time, cropland for feed falls by ~30% globally, while cropland for food drops by about ~15% — smaller, but still substantial.

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Strategies to reduce agricultural land use (=proxy for biodiversity decline) at BAU diets and animal numbers (EU-relevant)

- **Agricultural grassland use reduction** where environmental benefits and yields allow (rewetting/rewilding on marginal grasslands; carbon-rich soils protection).
- **Reduce cropland for feed** by shifting monogastric rations towards by-products and safe recycled food waste streams.
- **Safeguard food cropland productivity** through agronomy (legumes, rotations, soil health) to avoid leaching.

Improve nutrient use and circularity

The fertilization strategies show a decisive shift from synthetic fertilisers to recycled sources (manures, food waste compost, human excreta, legumes) in optimisation runs (Figure 3). Globally, total N inputs remain above the 2020 baseline in the optimized circular scenario, but well below BAU, meaning circular sources replace synthetic N rather than add to it. In Europe, compared to the Base_2020 scenario, total N and P use fall by 13 and 15 %, respectively, in the optimised circular run, underscoring the potential of circularity under European conditions.

Strategies to improve nutrient cycling (EU-relevant)

- **Scaling biologically N-fixing legumes** using eco-schemes, and supporting N-fixing crops in diversified rotations.
- **Using food-waste-derived fertilisers**; enable cross-border trade of certified recycled nutrients.
- **Scale sanitised human-excreta fertilisers** where safe and acceptable.
- **Targeted mineral-N reduction** and replacing with circular fertilizers

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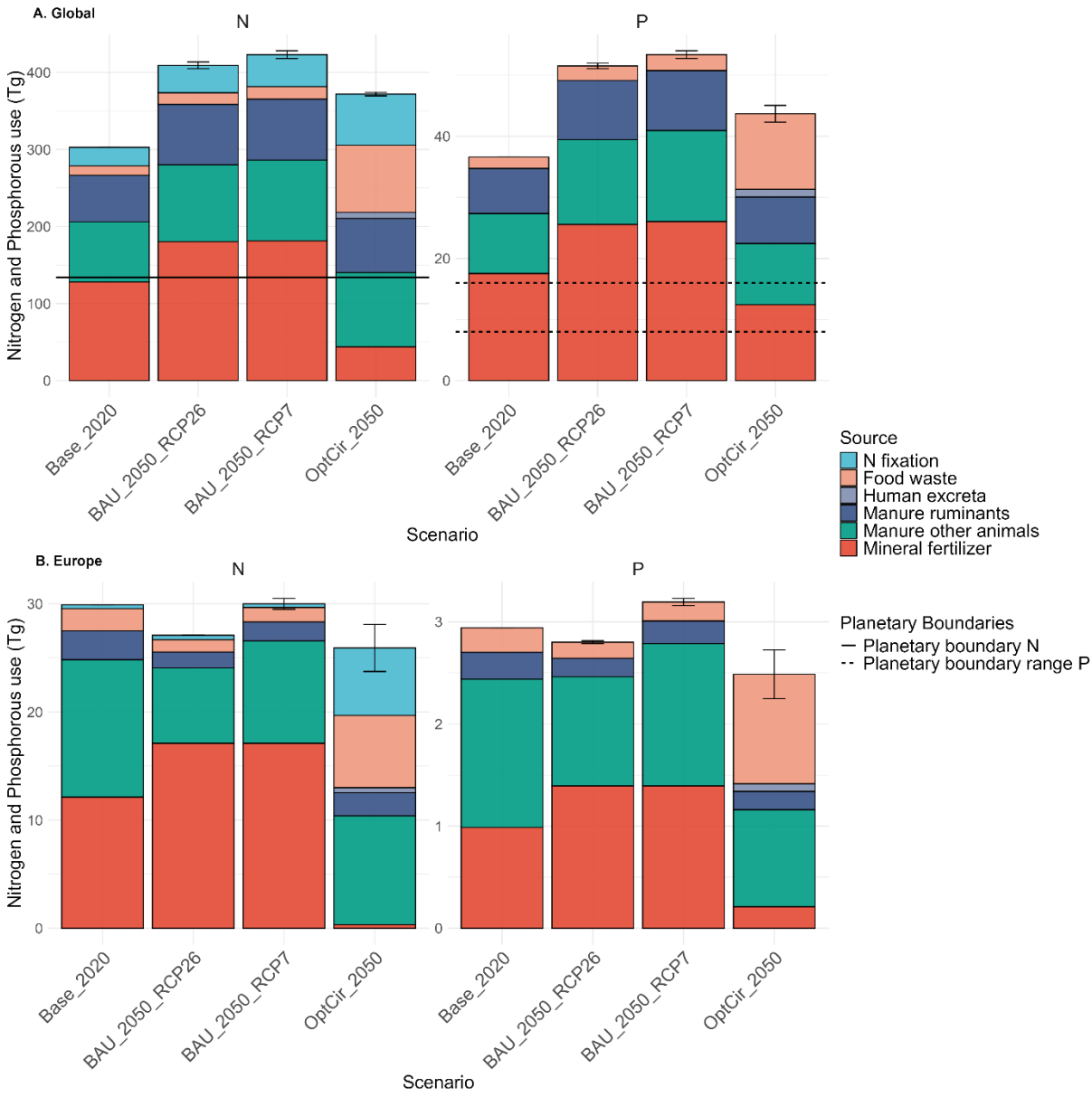

Figure 3. Nitrogen (N) and phosphorus (P) use by source for (top) Global and (bottom) Europe across scenario groups. Bars represent the mean nutrient use across general circulation models (GCMs), stacked by source (N fixation, food waste, human excreta, manure from ruminants, manure from other animals, and mineral fertilizer). Black error bars indicate the standard deviation across GCMs for the total nutrient use per scenario group. Horizontal dashed lines show the planetary boundary ranges for P, and the solid line indicates the planetary boundary for N. Scenario groups include the 2020 baseline (Base_2020), baseline projections for 2050 under climate pathways RCP7.0 and RCP2.6 (BAU_2050_RCP7, BAU_2050_RCP26), and the optimized scenario (OptCir_2050). Units: teragrams of nitrogen per year (Tg N yr^{-1}) and teragrams of phosphorus per year (Tg P yr^{-1}).

Improve feed circularity

The feeding strategies indicate, in the optimised circular scenario, a larger share of processing by-products and safe food waste in pigs and chickens (monogastric animals), with a reduction of food crops used as feed (Figure 4). This shift underpins the ~15%

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European reduction in cropland for feed and contributes to cropland GHGe cuts. Beef and dairy cows (ruminants) are primarily fed on grass and processing by-products in a circular scenario (Figure 4).

Strategies to improve animal feeding (EU-relevant)

- **Reduce arable food and feed crops** to monogastric animals in feed rations.
- **Reduce grass to an amount** that still provides a healthy feed ration for ruminant animals.
- **Expand the use of safe by-products** (e.g., oilseed cakes, bran, whey) as feed for all animal types.
- **Expand the use of safe food waste as feed**, especially for chickens and pigs (monogastric animals). The safe processing of specific food waste streams for chicken and pig feed (strict biosecurity; only heat-treated, traceable streams).

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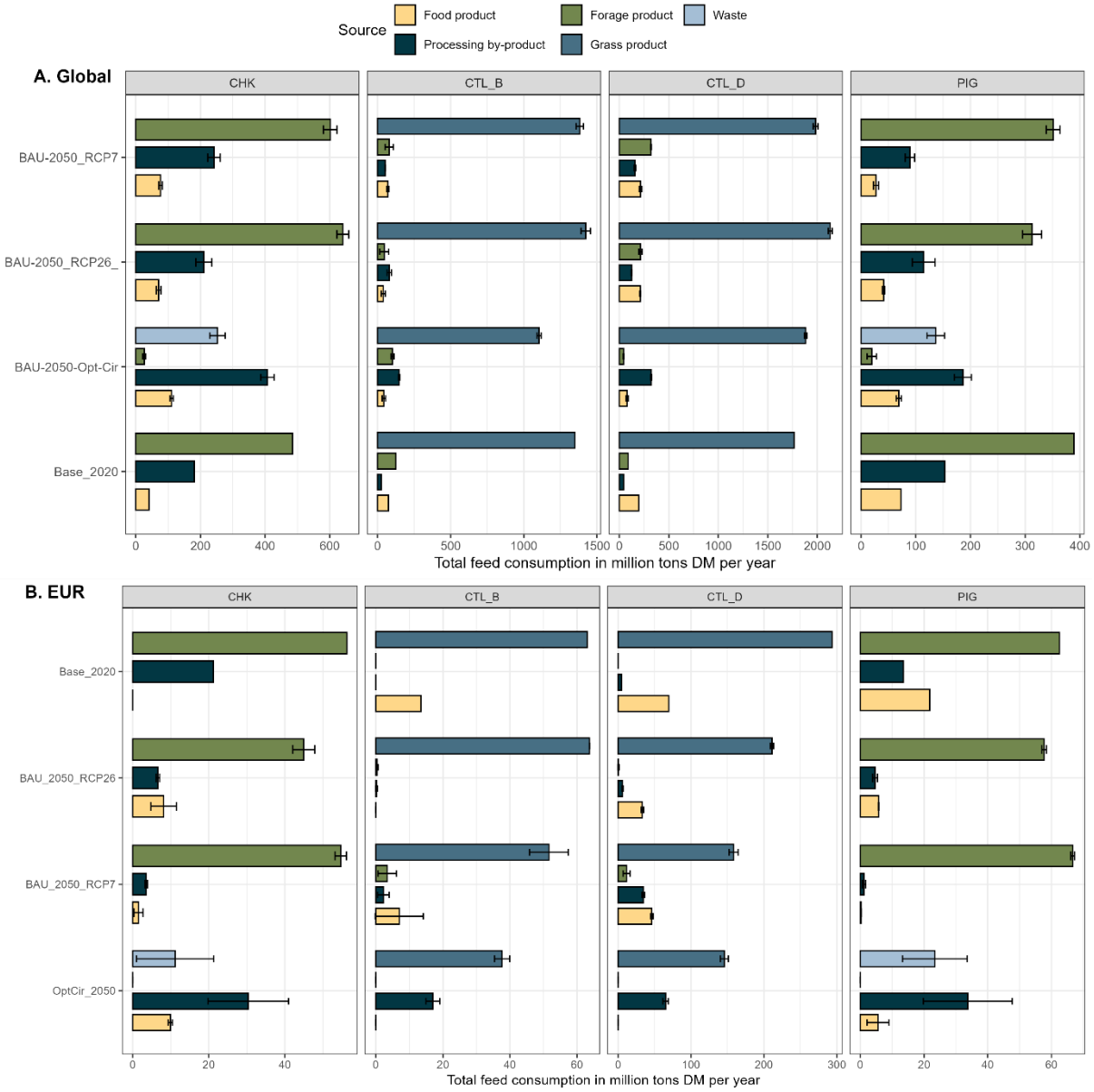

Figure 4. Feed consumption by livestock category for (A) Global and (B) Europe across scenario groups. Bars show mean annual feed use across general circulation models (GCMs), stacked by source (food products, forage products, grass products, processing by-products, and waste). Error bars indicate the standard deviation across GCMs for the total feed use per scenario group. Livestock categories include chickens (CHK), beef cattle (CTL_B), dairy cattle (CTL_D), and pigs (PIG). Scenario groups include the 2020 baseline (Base_2020), baseline projections for 2050 under climate pathways RCP2.6 and RCP7.0 (BAU_2050_RCP26, BAU_2050_RCP7), and the optimized scenario (OptCir_2050). Feed consumption is expressed in million tons of dry matter (DM) per year.

Reduce food loss and waste (FLW)

The waste breakdown shows that in optimised circular scenario, recycled waste increases strongly: by-products are almost entirely used for feed, food waste is mostly used as fertiliser (with a smaller share as feed), and post-harvest losses are used as fertiliser. This substantially supports the mineral fertiliser substitution and feed circularity described above (Figure 5).

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Strategies to improve waste and by-product handling (EU-relevant)

- **Maintain FLW-prevention targets**, but build collection and treatment systems that maximise nutrient and feed value of unavoidable waste.
- **Integrate FLW and nutrient policies** (e.g., municipal waste contracts that deliver fertiliser-grade outputs compatible with farm application windows).

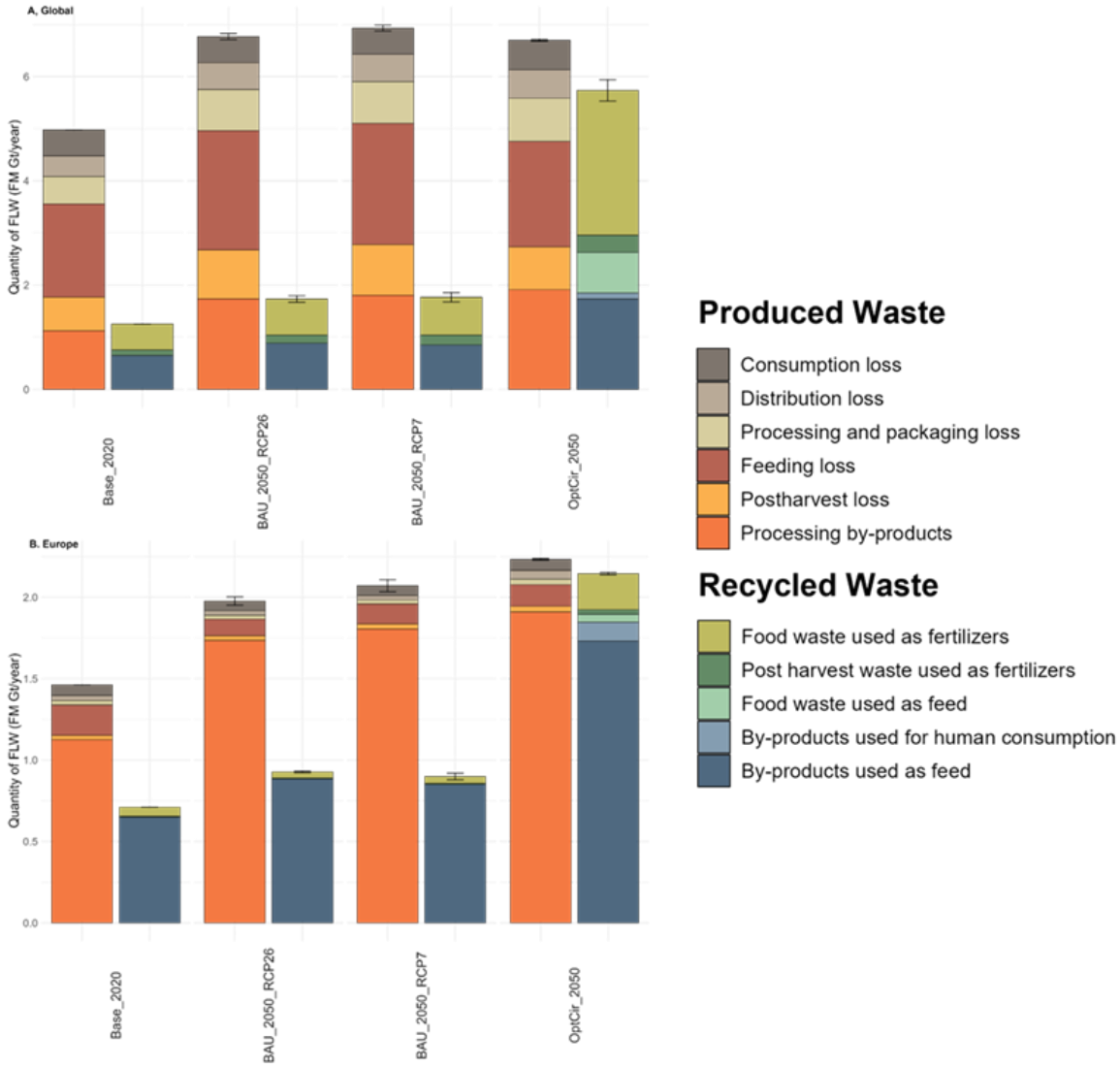

Figure 5. Fresh matter waste production and utilization for (top) Global and (bottom) Europe across scenario groups. Bars represent the mean annual amounts across general circulation models (GCMs), stacked by waste type (food waste, processing by-products, crop residues, manure, and other organic streams). Error bars indicate the standard deviation across GCMs for the total waste amount per scenario group. Scenario groups include the 2020 baseline (Base_2020), baseline projections for 2050 under climate pathways RCP2.6 and RCP7.0 (BAU_2050_RCP26, BAU_2050_RCP7), and the optimized scenario (OptCir_2050). Waste flows are expressed in gigatonnes of fresh matter per year (Gt FM yr^{-1}).

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Strategies to redesign the food system: Global vs. European?

- **Global-specific lever**: Rice methane abatement becomes significant only in rice-growing regions; it is not a major EU wedge.
- **Levers strong in both global and EU contexts**: Cropland N_2O reduction, grassland reduction/restoration, by-product- and safe food waste-based feed, and circular fertilisers.
- **EU-specific opportunities:** Larger relative GHG and land reductions in optimized circular scenario (–52% GHG; –38% land), robust regulatory capacity to certify recycled fertilisers and manage cross-border nutrient flows, and infrastructure to scale composting and precision agriculture.

Taken together, these levers deliver the large mitigation observed in the optimised circular scenario — 27% global GHG reduction and 39% global land-use reduction, with even larger proportional gains in Europe — while holding animal numbers and diets constant at baseline (2020) and BAU levels (2050).

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Discussion and Limitations

Robustness to climate projections.

Across the three GCMs used, variation in outcomes is slight, and the direction and magnitude of trends remain consistent. This suggests that our findings are robust to alternative climate projections, increasing confidence that the identified levers will be effective under a range of future climate projections. The circular scenario showed more variation between the GCMs. This is likely due to the increased solution space this scenario has due to less constraints (e.g., cropland could be freely optimized).

Minimizing emissions and their implications

In the optimized scenario optcir-2050, the objective function minimizes GHG emissions only. Consequently, the reported values for land use, nitrogen, and phosphorus are the co-outcomes at the GHG-optimal solution and do not represent their global minima. Tables 100 and 11 should not be read as independently optimized results for these indicators. Identifying the lowest achievable land use, total N, or P use would require separate single-objective runs for each metric or a formal multi-objective analysis. Related to this: Inferences about circularity's potential to reduce land use and nutrient pressures should be made cautiously and, ideally, should also be based on dedicated single-objective or multi-objective analyses (Table 11).

Biomass feeding gap and its implications on endogenous land use estimates

When fixing animal numbers and diets (BAU 2050), the CiFoS model shows a biomass gap in animal feeds. This gap likely arises because certain feed sources are not yet accounted for, including crop residues (which make up a substantial share of global feed), roadside grazing, and the use of common lands and backyard feeding, which is hard to quantify. To meet nutritional needs under these constraints, the model relies on higher land use, particularly grasslands. We are addressing these limitations in collaboration with Prof. Dr Mario Herrero's team at Cornell University and aim to provide improved estimates in the next deliverable 6.2. See also footnote [1] for more information.

Yield constraints

LPJmL modelled yields are water-limited but not nitrogen-limited. Modelling the yields with nitrogen limitations would likely yield more realistic yield patterns, especially in a global context were there are large yield gaps (e.g., sub-Saharan Africa). In this study, we therefore show potential yields in terms of nitrogen provision. This way of modelling also points to the importance of water management and drought resilience.

Scale and policy relevance

The model captures the major trends at aggregated spatial scales (Europe and 12 other world regions). To translate these insights into actionable policy, they should be complemented by higher-resolution spatial and temporal analyses (e.g., field/farm/national/regional models for nutrients and water, and land-use assessments) that can test feasibility, costs, and identify trade-offs and benefits across scales and multiple objectives.

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Outlook

In this task 6.1, we modelled livestock baseline scenarios and optimized only some parts of the food systems while keeping diets and animal numbers constant. In task 6.2 of the Re-Livestock projects, we will evaluate adaptation and mitigation strategies for livestock production systems under changing climate conditions and future time periods (2020/2050). This can include innovations in land management, manure management, nutrient management, feeding, cropping, assessing their combined potential to achieve sustainable, climate-resilient livestock systems in Europe and their implications for global supply chains.

5. Conclusions

Our linkage of CiFoS with LPJmL delivered a 2020 base run and RCP-based 2050 baselines (three GCMs) for livestock systems under constant animal numbers and fixed human diets. Across these baselines, global impacts tend to rise, while Europe shows moderate declines in several indicators. When we optimise biomass flows according to circular principles—substituting synthetic fertilisers with recycled nutrients, reallocating feed toward processing by-products and safe recycled food waste streams, and freeing land (especially grassland and feed crops)—environmental pressures fall substantially even without changing herds or diets. Globally, this translates into lower GHG emissions and markedly reduced land use; in Europe, the proportional reductions are larger, reflecting a strong potential for reducing environmental impacts. Differences across GCMs are small, indicating that the direction and magnitude of these improvements are robust to climate-model choice, while RCP differences mainly scale the size of the challenge that circularity can offset.

Taken together, the results identify clear levers for EU context: halve cropland N_2O through reduced mineral-N use, food waste as fertilizer and legume expansion, scale high-quality recycled fertilisers and manure management, shift monogastric feed toward by-products with strict safety for any recycled food streams, and prioritise restoration of marginal grasslands while protecting productive food cropland. Deliverable 6.1 thus provides the linked data pipeline and the RCP baselines needed to design actionable pathways. In Deliverable 6.2, we will assess adaptation and mitigation innovations—including dietary change (e.g., EAT-Lancet) and management practices—to translate these insights into climate-resilient livestock strategies for Europe within the context of a globally coherent food system.

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6. Project Outputs

Model Documentation

Overview

As part of strengthening the reliability, transparency, and usability of the Global Circular Food System (CiFoS) model, a complete and structured model documentation was developed. This resource is crucial for ensuring that the model can be understood, verified, and used effectively by both current and future researchers. It supports reproducibility, facilitates onboarding of new team members, and enables external reviewers to assess the scientific robustness of the model.

Purpose

The documentation serves four key purposes:

- **Transparency** — Clearly outlines the equations, parameters, variables, and assumptions used in the standard *Global-CiFoS_v1.0* configuration.
- **Reliability** — Provides a single, authoritative reference for model formulation, data sources, and scenario design.
- **Reproducibility** — Allows other researchers to replicate or at least understand model runs, understand dependencies, and verify outputs.
- **Collaboration** — Functions as a living reference, supporting both internal development and external research collaborations.

Scope and Content

The documentation is structured as an interactive Quarto book with multiple parts:

- **Model Description** — Conceptual overview of model subsystems, circular nutrient flows, and environmental optimization logic.
- **Model Formulation** — Full set definitions, parameter lists, variable descriptions, and mathematical equations, distinguishing between *core* and *scenario-dependent* constraints.
- **Scenarios** — Description of scenario switches and policy levers.
- **Model Data** — Detailed mapping between GAMS parameters, Excel input sheets, and source references.
- **Output and Validation** — Indicator definitions, sensitivity analyses, and validation checks.
- **Execution & Team Practices** — Instructions for running the model locally or on HPC, and collaborative Git workflows.

Methods

- Extracted all relevant model code from the CiFoS GAMS implementation and systematically organized it into thematic documentation sections.
- Linked equations to input data and source references for traceability.
- Integrated diagrams, tables, and cross-references for clarity.
- Implemented a versioning system to reflect model updates.

Added Value

Although not an original contractual deliverable, the model documentation:

- **Directly improves model credibility** by making its internal logic and assumptions transparent.

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- **Reduces onboarding time** for new contributors by providing a clear entry point into model structure and data flows.
- **Supports external engagement** with policymakers, researchers, and stakeholders by making the model's workings accessible.
- **Future-proofs the model** by ensuring knowledge continuity beyond individual contributors.

Deliverable Specifications

- **Title:** *Model Documentation: Global Circular Food System (CiFoS) Model*
- **Format:** Quarto book (HTML & PDF export)
- **Length:** ~200 pages
- **Version:** 1.0 (May 2025)
- **Authors:** Wolfram J. Simon (lead), Laura Gerwien, Vera Bekkers, Alejandro Parodi Parodi, Thomas Maindl, Hannah van Zanten
- **Status:** Completed and hosted on the project's documentation platform.

Conferences and Workshops

- Invited speaker in St. Malo 2025 and collaborator on a white paper about the future of livestock production systems.
- Speaker at EAAP 2025 in the session "Joint session of the Animal Task Force & the EAAP Commission on Livestock Farming Systems: Livestock farming systems for the next generation: can we imagine the future?" Our presentation was titled " Challenge voice – Thinking the future food systems." Wolfram Simon had to attend the panel discussion as "the challenging voice". In this lively discussion, he could make use of the novel required knowledge from the work done for this deliverable.

Lectures and webinars

- Lecture and computer practical on model-based food system redesigns in a master's course at Wageningen University on circular food systems and livestock production systems.
- Webinar on circular food systems and livestock production systems for the Re-Livestock project.

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