Agora
Agriculture

ANNEX

Agriculture, forestry and food in a climate neutral EU

The land use sectors as part of a sustainable food system and bioeconomy

Content

This Annex belongs to the study: Agora Agriculture (2024): Agriculture, forestry and food in a climate neutral EU. The land use sectors as part of a sustainable food system and bioeconomy.

List of abbreviations

AGB	Aboveground Biomass
AR4	4th assessment report of the IPCC
AR5	5th assessment report of the IPCC
BGB	Belowground Biomass
BKG	Bundesamt für Kartografie und Geodäsie
BMEL	Bundesministerium für Ernährung und Landwirtschaft, Federal Ministry of Food and Agriculture
BMI	Body mass index
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalised Impact
CBI	Carbon Balance Indicator
CH_4	Methane
CLC	Corine Land Cover
CO_2	Carbon Dioxide
CO_2eq	Equivalent of Carbon Dioxide (the amount of carbon dioxide that would cause the same radiative forcing as the greenhouse gases in question)
DACCS	Direct Air Carbon Capture and Storage
DBFZ	German Institute for Biomass Research
EEA	European Environment Agency
EFs	Emission Factors
EFSA	European Food Safety Authority
EU	European Union (here: EU-27)
FADN	Farm Accountancy Data Network
FAO	Food and Agriculture Organization
FNR	Fachagentur Nachwachsende Rohstoffe e. V.
FGT	Fast-growing trees

GNB	Gross Nitrogen Balance
GW	Gigawatt
GWh	Gigawatt-hour
GWP_{100}	Global Warming Potential over 100 years
ha	Hectare
HWP	Harvested Wood Product
IPCC	Intergovernmental Panel on Climate Change
kcal	Kilocalorie
kg	Kilogramme
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V.
KWh	Kilowatt-hour
Lfl	Bayerische Landesanstalt für Landwirtschaft Institut für Betriebswirtschaft und Agrarstruktur, Bavarian State Research Center for Agriculture
LSU	Livestock units
m^3	Cubic meter
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt-hour
N_2O	Nitrous Oxide
NDA	Panel on Nutrition, Novel Foods and Food Allergens
NH_3	Ammonia
NUTS	Nomenclature of Territorial Units for Statistics (a geocode standard for referencing subdivisions of countries for statistical purposes in the EU, e.g., NUTS-2: Nomenclature of Territorial Units for Statistics, Level 2)
OECD	Organisation for Economic Co-operation and Development
PHD	Planetary Health Diet
PMP	Positive Mathematical Programming
PPP	Plant Protection Products
PV	Photovoltaics

SSPs	Shared Socioeconomic Pathways
SMEKUL	Sächsisches Staatsministerium für Energie, Klimaschutz, Umwelt und Landwirtschaft
SLF	semi-natural landscape features
StMELF	Bayerisches Staatsministerium für Ernährung, Landwirtschaft, Forsten und Tourismus, Bavarian State Ministry of Food, Agriculture, Forestry and Tourism
TW	Terawatt
TWh	Terawatt-hour
UAA	Utilised Agricultural Area
UNFCCC	United Nations Framework Convention on Climate Change
VSET	Voluntary Set-Aside
WBAE	Wissenschaftlicher Beirat für Agrarpolitik, Ernährung und gesundheitlichen Verbraucherschutz beim Bundesministerium für Ernährung und Landwirtschaft, Scientific Advisory Board on Agricultural Policy, Food and Consumer Health Protection at the Federal Ministry of Food and Agriculture

1 The CAPRI modelling system

The Common Agricultural Policy Regionalised Impact (CAPRI) modelling system (Gocht & Witzke 2022) is an open source global agricultural sector model with focus on the EU-27. It provides a detailed depiction of technical and economic mechanisms in the agricultural sector, as well as strong linkages to the biophysical environment of agriculture. The supply module includes 215 NUTS-2 regions[1] within the EU-27 and many more in neighbouring countries. For each of these regions, the model optimises an objective income function "revenue minus costs" under environmental, legislative and resource constraints. Crop and animal production are depicted by about 60 "activities", i.e., single or grouped crops and animals.

Usually, the model is used for ex-ante policy impact assessments comparing two future scenarios, one with and one without a specific policy. For this study we use the model to translate our set of assumptions, such as environmental constraints and political framework conditions, into an agricultural production pattern that is both 1) technically consistent and 2) economically optimal within the boundaries set by our modelling inputs.

Detailed information on how CAPRI works can be found in CAPRI model documentation (2022).

1.1 The CAPRI database

The CAPRI network integrates and systematically processes existing data from various sources. CAPRI produces a distinctive reference and projection dataset that is unparalleled in Europe. To guarantee the comparability of the results between the member states and over time, CAPRI uses standardised and harmonised data sources from Eurostat, the European Commission, the Food and Agriculture Organization (FAO) and the Organisation for Economic Co-operation and Development (OECD) whenever possible. A significant portion of model development is dedicated to data preparation and standardisation to reference units, ensuring that the data remains comparable both over time and across European regions. The database consolidation process is designed to allow for the integration of new or improved data sets and statistics, ensuring that all data changes can be replicated systematically. This approach enables the continuous development of data consolidation without introducing methodological inconsistencies.

The result of the database consolidation process is a comprehensive time series for the agricultural sector at NUTS-2 level for production activities covered by the Economic Accounts for Agriculture[2], for land use, livestock density, factor income, prices, market balances, nutrient requirements and nutrient suppliers. In addition, the time series contains a consistent depiction of regional feed requirements and feed resources. In addition to economic outputs, CAPRI also provides environmental indicators, i.e., for greenhouse gas (GHG) emissions and nutrient balances. Statistical or mathematical estimation methods are used for data consolidation to adjust the statistical values only if economic and biophysical correlations or other statistics require this. If, for example, the modelled production quantity (yield multiplied by cropping area) does not match the production quantity from the official statistics, the yield is adjusted accordingly. The original and the new estimated data are stored together for comparison and better traceability. A metadata model allows information on the statistics and processing steps to be summarised and stored efficiently.

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[1] NUTS = Nomenclature of territorial units for statistics

[2] https://ec.europa.eu/eurostat/cache/metadata/en/aact_esms.htm (accessed 22.08.2024).

1.2 Baseline projection

General approach

Projecting into the future involves using statistical projection methods that combine default trends obtained from time-series data, technical constraints and external inputs. The comprehensive time series from the CAPRI database is used to establish future trends and reference points for future analysis. However, updating the time series is challenging due to the coverage of approximately 270 regions. Data delivery at the regional level is often delayed, making it challenging to consistently cover recent years in the model. Consequently, statistical information that is already available at national level may not be fully reflected in CAPRI. To fill data gaps, short-term projections are created in CAPRI in addition to medium and long-term projections. This implies that official statistics are only partially consistent with the short-term projections used as data points for 2020.

Future projections for any given point in time are commonly referred to as "baselines". The CAPRI baseline uses official projections from the medium-term outlook of the European Commission generated with the Aglink modelling system, trend projections from historical data in the CAPRI database as well as projections for the Shared Socioeconomic Pathways (SSPs) from the GLOBIOM[3] and PRIMES[4] models. The medium-term EU projections cover a period of approximately ten years and are widely used as reference data in various European analyses on the agricultural sector and environmental dimensions. Data from GLOBIOM and PRIMES cover a longer term. GLOBIOM provides long-term spatially-explicit projections on production and yields of different crops. At the time when the baseline for this study was created, GLOBIOM projections did not yet comprehensively include the effects of future climate change and thus may underestimate the impact of climate change on yields.

Adaptation for longer time horizons through positive mathematical programming

Our study simulates a long adjustment period up to the year 2045. A longer time horizon allows for greater flexibility in supply responses, as producers have more time to adjust their production factors and adapt their strategies: they can optimize their allocation of resources, adopt new technologies and adjust their production in response to market signals and policy changes. To take this into account, the CAPRI supply model is adjusted to be more flexible, reflecting a long-term supply response. Technically, this is achieved by halving the cost function slope of the Positive Mathematical Programming (PMP) term for all products.

The regional optimisation models in CAPRI are calibrated using PMP. PMP helps to model how producers respond to policy changes and market developments. Calibrating the model enhances accuracy by better aligning observed patterns with calculated solutions. For this study, PMP and extended PMP approaches with estimated regionalised supply elasticities were used to calibrate the supply models of 270 regions (Jansson & Heckelei 2011).

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[3] https://globiom.org/index.html (accessed 22.08.2024)
[4] https://e3modelling.com/modelling-tools/primes/ (accessed 22.08.2024)

1.3 Further measures implemented

For our scenario, a couple of overarching measures are implemented in the CAPRI modelling on top of the sectoral modelling inputs described in subsequent chapters.

The basic payment scheme of the Common Agricultural Policy (CAP) remains but is adjusted for inflation. In our modelling, this policy serves as a placeholder for more targeted instruments to remunerate public goods provided by agriculture. Voluntary coupled support is eliminated to avoid perpetuating the market distortions created by this policy.

A tax on GHG emissions of 200 euro per tonne carbon dioxide equivalent (CO_2eq) is set to incentivise the uptake of mitigation measures and lead to economically efficient changes in production processes. The price is at the lower end of the range for long-term costs of Direct Air Carbon Capture and Storage (DACCS) projected by different studies. If we assume that DACCS is needed to reach climate neutrality, its cost can be assumed to be the marginal abatement cost; projections range from under 100 euro per tonne of CO_2 captured and stored to over 1000 euro per tonne, with average values between 200 and 300 euro per tonne (Breitschopf et al. 2023, IEA 2022, Reiner et al. 2022).

The CAPRI baseline predicts a decrease in agricultural land in Europe and Germany by 2045, mainly because of the expansion of settlement areas. This estimate is based on past decreases. However, it is expected that agricultural land in Germany will not decline at the same rate as in the past, due to a decrease in surface sealing by settlement. Also, we have explicit assumptions on afforestation at the expense of agricultural land that are different from the CAPRI results. As a result, we anticipate a minimal value for Utilised Agricultural Area (UAA) in Germany corresponding to 101% of the CAPRI 2045 baseline projection, which is set as a lower bound in modelling. Likewise, our assumptions for settlement expansion and afforestation in other European regions translate into a lower bound of 98% of CAPRI 2045 baseline values for UAA.

The CAPRI land use category of "Voluntary Set-Aside" (VSET) is reduced to a technical minimum. Our approach on the establishment and spatial pattern of semi-natural landscape features in our 2045 scenario is documented in Annex Chapter 6.3.

Fallow land is fixed within a specific range by NUTS-2 region relative to the year 2020, preventing the model from excessively fallowing arable land. This approach is based on the assumption that a combination of different political measures will prevent fallow land areas to be much larger than today.

No trend projections are assumed for organic agriculture as the scenario depicts the development of agriculture on average and does not distinguish between agricultural systems.

First-generation-biofuel mandates are phased out completely. Additional supply curve adjustments are implemented to disincentivise the export of first-generation biofuels. We expect the biofuel demand to be largely covered by second-generation biofuels.

2 Greenhouse gas, land use and virtual land trade balances (Chapter 4.2)

2.1 Calculation and calibration of greenhouse gas balances

Greenhouse gas (GHG) emissions figures reported in the study stem from different sources. With a few exceptions, CAPRI results that have undergone a post-modelling calibration are reported. Here, an overview of how individual figures are calculated and details about the calibration are presented. Also, the classification/aggregation used for reporting our results is explained here.

The CAPRI model reports GHG emissions linked to the modelled agricultural activities in the 2045 scenario and in 2020. For 2020, these figures are different from GHG emissions officially reported by EU member states. This is due to four reasons:

1. CAPRI uses values for the Global Warming Potential over 100 years (GWP_{100}) for methane (CH_4) and nitrous oxide (N_2O) from the 4th Assessment Report of the IPCC (AR4) while official reporting to United Nations Framework Convention on Climate Change (UNFCCC) now uses the factors from the 5th Assessment Report (AR5).
2. Agricultural activities in CAPRI for 2020 stem from a baseline calibration.
3. CAPRI has different assumptions about the exact nature of production processes and, for example, volumes of fodder or manure linked to them.
4. CAPRI emission figures are calculated by the model based on a uniform approach for every CAPRI region, while EU member states use different methods for their reporting.

The difference to officially reported GHG figures makes CAPRI results difficult to compare to other studies and future GHG projections. Through a calibration, we aim to achieve this comparability. A similar approach is used in the projection of GHG emissions by the European Commission.

Short method description

GHG emissions figures that belong to category "3. Agriculture" of the UNFCCC Common Reporting Format, are derived from CAPRI for 2020 and the 2045 scenario and first translated into carbon dioxide equivalent (CO_2eq) so that the CAPRI figures for 2020 match, on aggregate, officially reported GHG emissions for the same year.

Data

Data is extracted from CAPRI results for most emission sub-categories. Emissions from agricultural peatlands are calculated with activity data from CAPRI and emission factors from IPCC (2014) (see Annex Chapter 7.1 for details).

Calculation and classification

Table A1 summarizes all emission categories/sub-sectors, how they were classified for presentation in this study, and how the GHG emission figures were calculated for each of them.

Calculation and representation of GHG emission figures by sub-sector → Table A1

CAPRI indicator or own indicator from side calculation	UNFCCC Common Reporting Format category	Classification/ category of aggregation for this study	Calculation method applied
CH_4 emissions from enteric fermentation	3.A Enteric Fermentation	Emissions from livestock and manure	Scaled CAPRI results
Indirect N_2O emissions from volatilization (manure management)	3.B Manure Management	Emissions from livestock and manure	Scaled CAPRI results
N_2O emissions from manure management (housing and storage)	3.B Manure Management	Emissions from livestock and manure	Scaled CAPRI results
CH_4 emissions from manure management (housing and storage)	3.B Manure Management	Emissions from livestock and manure	Scaled CAPRI results
CH_4 emissions from rice production	3.C Rice Cultivation	Other emissions from agriculture	Scaled CAPRI results
N_2O emissions from crop residues	3.D.1 Direct N_2O Emissions From Managed Soils	Emissions from agricultural soils	Scaled CAPRI results
N_2O emissions from mineral fertilizer application	3.D.1 Direct N_2O Emissions From Managed Soils	Emissions from agricultural soils	Scaled CAPRI results
N_2O emissions from grazing	3.D.1 Direct N_2O Emissions From Managed Soils	Emissions from livestock and manure	Scaled CAPRI results
N_2O emissions from manure application	3.D.1 Direct N_2O Emissions From Managed Soils	Emissions from livestock and manure	Scaled CAPRI results
N_2O emissions from the cultivation of organic soils	3.D.1 Direct N_2O Emissions From Managed Soils	Emissions from peatland	Own method for calculation
Indirect N_2O emissions from leaching and runoff	3.D.2 Indirect N_2O Emissions From Managed Soils	Emissions from agricultural soils	Scaled CAPRI results
N_2O emissions from volatilization (agricultural soils)	3.D.2 Indirect N_2O Emissions From Managed Soils	Emissions from agricultural soils	Scaled CAPRI results
CH_4 from field burning of agricultural residues	3.F Field Burning of Agricultural Residues	Other emissions from agriculture	Figures for 2020 from official reporting; assumed to be zero in 2045
N_2O from field burning of agricultural residues	3.F Field Burning of Agricultural Residues	Other emissions from agriculture	Figures for 2020 from official reporting; assumed to be zero in 2045
CO_2 emissions from liming	3.G Liming	Other emissions from agriculture	Scaled CAPRI results
CO_2 emissions from urea application	3.H Urea Application	Other emissions from agriculture	Scaled CAPRI results
CO_2 emissions from other carbon-containing fertilizers	3.I Other Carbon-containing Fertilizers	Other emissions from agriculture	Figures for 2020 from official reporting;

			assumed to be zero in 2045
Other (all gases)	3.J Other	Other emissions from agriculture	Official figures for 2020; copied for 2045
CO_2 emissions from total organic soils	Under LULUCF	Emissions from peatland	Own method for calculation
CH_4 emissions from total organic soils	Under LULUCF	Emissions from peatland	Own method for calculation

The scaling process of CAPRI results is conducted as follows:

1. CAPRI results are translated into GWP_{100} values according to AR5: A value of 28 gramme CO_2eq per gramme of CH_4 and a value of 265 gramme CO_2eq per gramme of N_2O is applied (IPCC 2013).

2. Discrepancies between CAPRI results for 2020 and officially reported GHG emission figures for 2020 (2023 submission) are translated into scaling factors by EU member state and by gas:

$$SF_{ij} = \frac{\sum_k UNFCCC_{ijk,2020}}{\sum_k CAPRI_{ijk,2020}}$$

   where SF_{ij} is the scaling factor for gas i and EU member state j, $UNFCCC_{ijk,2020}$ are officially reported GHG emissions for 2020 under sector "3. Agriculture" for gas i by EU member state j and sub-sector k, and $CAPRI_{ijk,2020}$ are CAPRI results for GHG emissions in 2020 for gas i, EU member state j and sub-sector k, expressed in CO_2eq according to AR5.
   This means that the agricultural emissions for CH_4, N_2O and CO_2 are summed up (separately for each gas) before scaling factors are calculated. This way, the ratio between GHG emissions of different sub-sectors for the same gas is kept intact through the scaling process.

3. These scaling factors are then used to scale CAPRI results for both 2020 and 2045:

$$Result_{ijkx} = SF_{ij} * \ CAPRI_{ijkx}$$

   where $Result_{ijkx}$ is the result of the scaling process of for GHG emissions of gas i in EU member state j for sub-sector k in year x; x is either 2020 or 2045.

When summed up over member states and sub-sectors, this results in the value of the GHG emissions reported for 2020 on aggregate although the results for individual sub-sectors or aggregation categories do not match.

When no CAPRI results are available, figures from official GHG reporting are used for 2020. We assume that the practices of using carbon-containing fertiliser other than urea as well as field burning of agricultural residues will be phased out by 2045. Therefore, GHG emissions from these sub-sectors are set to zero for 2045.

Emission figures for UNFCCC category 3.J are largely attributable to fugitive emissions from biogas installations. Because we assume biogas production to be stable over time, 2020 emission figures are copied to 2045.

The classification used in the presentation of results differs from the UNFCCC Common Reporting Format in two points:

1. N_2O emissions from manure application is grouped under "Emissions from livestock and manure" instead of "Emissions from agricultural soils". This is justified by the fact that a large part of these emissions can be

avoided by reducing livestock numbers or making technological changes in manure management.

2. N_2O emissions from organic soils are subsumed under "Emissions from peatland" instead of "Emissions from agricultural soils". This underlines that these emissions can be avoided by rewetting agricultural peatlands.

Results

Unscaled and scaled figures for the individual sub-sectors and the different aggregation levels are depicted in Table A2.

Unscaled and scaled GHG emissions → Table A2

Aggregation categories and individual sub-sectors	Emissions ($MtCO_2eq$)					
	2020		2045 main scenario		2045 without food consumption shift	
	CAPRI original	Final results	CAPRI original	Final results	CAPRI original	Final results
Emissions from agricultural soils	**89.66**	**77.60**	**53.18**	**47.00**	**61.36**	**54.39**
Indirect N_2O emissions from leaching and runoff	7.13	6.21	2.42	2.16	3.25	2.84
N_2O emissions from crop residues	33.04	28.41	23.81	21.01	25.15	22.13
N_2O emissions from mineral fertilizer application	44.15	38.42	22.98	20.37	27.44	24.66
N_2O emissions from volatilization (agricultural soils)	5.35	4.57	3.98	3.45	5.53	4.76
Emissions from livestock and manure	**287.17**	**281.53**	**94.77**	**93.19**	**144.11**	**140.55**
Indirect N_2O emissions from volatilization (manure management)	4.53	3.97	2.11	1.85	3.56	3.08
CH_4 emissions from enteric fermentation	185.98	189.63	67.23	69.03	98.12	100.99
CH_4 emissions from manure management (housing and storage)	39.61	40.06	6.61	6.57	9.51	9.55
N_2O emissions from grazing	18.43	14.36	7.94	6.26	14.24	10.84
N_2O emissions from manure application	22.96	19.87	6.16	5.32	11.46	9.78
N_2O emissions from manure management (housing and storage)	15.67	13.64	4.72	4.16	7.21	6.31

Emissions from peatland		**108.01**		**35.84**		**35.84**
CO_2 emissions from total organic soils		91.47		17.73		17.73
CH_4 emissions from total organic soils		4.84		17.53		17.53
N_2O emissions from total organic soils	8.22	11.70		0.58		0.58
Other emissions from agriculture	**13.04**	**15.34**	**10.03**	**10.34**	**10.52**	**10.84**
CH_4 emissions, other (3.J)		1.50		1.50		1.50
CO_2 emissions from liming	8.12	6.42	7.77	6.13	7.87	6.22
CO_2 emissions from urea application	2.63	2.78	1.50	1.59	1.80	1.89
CH_4 emissions from rice production	2.29	2.69	0.76	0.90	0.85	1.01
N_2O emissions, other (3.J)		0.23		0.23		0.23
CH_4 emissions from field burning of agricultural residues		0.74		0.00		0.00
N_2O emissions from field burning of agricultural residues		0.21		0.00		0.00
CO_2 emissions from other carbon-containing fertilizers		0.77		0.00		0.00
Total of scaled sub-sectors	**389.88**	**371.02**	**157.97**	**148.79**	**215.98**	**204.06**
Grand total	**398.09**	**482.49**	**166.03**	**186.36**	**224.10**	**241.63**

2.2 Greenhouse gas emissions reductions through ground-mounted solar photovoltaics

We illustrate the potential of emissions reduction through the additional installed capacity of solar PV in 2045, which is 612 gigawatt (GW).

Short method description

We calculate the avoided emissions very roughly using the emission factors of today's EU energy mix. We further assume a power production of 1 000 gigawatt hours (GWh) per year resulting from each GW of solar photovoltaics (PV) capacity.

Data

Based on data from EMBER (2024), the emission factor of today's energy mix is 255.6 g CO_2eq per kilowatt-hour (kWh), while it is 48 g CO_2eq per kWh for solar PV, resulting in avoided emissions of 207.6 g CO_2eq per kWh.

Calculation

The emission factor of today's energy mix is calculated by weighting the emission factors of today's energy sources with their share in today's energy mix. Total avoided emissions are calculated by multiplying the avoided emissions per kWh with the amount of energy of 612 terawatt hours (TWh) produced with the additional capacity.

Results

On this basis, the additional installed capacity of ground-mounted solar PV would save 127 $MtCO_2$eq per year.

2.3 Land use balance in the EU in 2020 and 2045

This chapter shows how the distribution of land use in the EU evolves between 2020 and 2045 as a result of our scenario. It describes the assumptions and method underlying the projection of changes in each land use category over time. The land use categories we consider are: agricultural land, forest land, settlements, PV area and other land.[5] In view of its importance for the energy transition and the significant land requirements compared to other power generation systems, ground-mounted solar PV is included in this list although it is not a separate land use category in GHG reporting.

Short method description

Land use in 2045 and the implied land-use change between 2020 and 2045 is exogenously determined according to assumptions on afforestation, the development of settlements and PV expansion as well as the assumption of preservation of permanent grassland. The resulting available area for cropland is a constraint for the CAPRI modelling of arable agricultural production.

Data and calculation

We assume 5 million hectares of afforestation at the expense of agricultural land. For settlements, we first extrapolate the 2015 to 2020 trend to 2020–2030 based on land use data from GHG reporting (European Union 2023). For 2030–2045 the trend is based on the example of the German Sustainable Development Strategy (Bundesregierung 2021). This strategy limits the land-use change to settlements to a maximum of 30 hectares

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[5] "Other land" corresponds to the IPCC classification "Other Land". It includes bare soil, rock, ice, and all land areas other than forest land, cropland, grassland, wetlands or settlements (Bickel et al. 2006).

per day, a ceiling which is upscaled to the EU level. Other land also slightly decreases to the benefit of settlements.

For solar PV, we use projections by Agora Energiewende (2023), according to which 612 GW of installed ground-mounted PV capacity is added by 2045. Together with the existing installed capacity of 99 GW, a total 711 GW will be in place. This capacity is distributed among member states based on their gross domestic product (Eurostat 2024b).

The national PV capacities are then allocated to four different categories of PV systems (conventional PV, PV on rewetted peatland, agri PV and biodiversity PV, enabling a combination of power generation, agricultural production and biodiversity enhancement). Member states with a larger area of rewetted peatland have a higher share of peatland PV, however, it does not exceed 30% of the national allocation and 5% of the rewetted peatland per country. Biodiversity PV together with agri PV do not exceed 50% of total national ground-mounted PV. The PV area of each category is calculated using the following power yields: 1 megawatt (MW) per hectare for conventional PV, 0.75 MW per hectare for PV on rewetted peatland and biodiversity PV, 0.5 MW per hectare for agri PV.

The additional installed capacity of 612 GW of solar power translates into 0.75 million hectares, of which only 0.38 million hectares of conventional PV is accounted as a land-use change (other PV categories remain agricultural land).

Results

Land use and land-use changes between 2020 and 2045

→ Table A3

Land use categories	2020 (million ha)	2045 (million ha)	Change (million ha)
Forest land	159.56	164.56	+5.00
Agricultural land	161.79	154.13	-7.66
Settlement	28.00	30.41	+2.41
PV area	0.12	0.50	+0.38
Other land	12.28	12.15	-0.13

2.4 Virtual land trade

A virtual land trade balance translates trade flows to and from a geographic region into the land area needed to produce those traded products. In the scientific literature, crop yields in the respective countries of origin of the traded products are often used to calculate virtual land trade balances (e.g., De Laurentiis et al. 2024). This approach has implications: the land embedded in specific trade flows is well depicted. But if the purpose of the analysis is calculating a development of virtual land trade for a given country over time, changes in international trade patterns may affect the virtual trade balance, even if the quantities of imports and exports of that country do not change. This is because at any given moment in time, the virtual land balance depends on whether the country of origin of traded products has a relatively high or low yield per hectare. For example:

1. A country imports 10 tonnes of wheat and exports 10 tonnes of wheat. In terms of wheat quantity, the net trade balance of this country for wheat would be zero.

2. Assume the yield level in the importing country is 10 tonnes per hectare while the yield level in the exporting country of origin is 5 tonnes per hectare. In this case, the importing country would be considered a net land importer of 1 hectare.
3. Conversely, if the yield level in the importing country is 5 tonnes per hectare and the yield level in the exporting country of origin would be 10 tonnes per hectare, the importing country would be considered a net land exporter of 1 hectare.

In other words, a country's net land imports are higher when its domestic yield levels are greater and the yield levels in the country of origin are lower. Thus, shifting imports from lower yield to higher yield origins would reduce virtual land imports.

Another potential drawback of using yield levels in the countries of origin arises when virtual land trade balances are interpreted such that net importers of virtual land would "take more than they give", while net exporters of virtual land "give more than they take". The above example shows that this interpretation can be misleading.

In order to meet this conceptual challenge, we calculate virtual land trade balances for 2020 and 2045 based on world average yields. According to this calculation, the EU's net virtual land trade for the year 2020 is -1 million hectares. This means that the land areas associated with the EU's export and import of agricultural products are nearly balanced when calculated on the basis of world average yields. Our 2045 scenario has a net virtual land trade of 21 million hectares. This means that if the EU's export and import quantities in 2045 are translated into virtual land using world average yields, the EU's virtual land exports would substantially exceed virtual land imports.

Short method description

All trade flows involving plant material from agriculture are translated into virtual land using their respective world average yields. Some imports are not considered, as there is no yield data for them: those of ready-to-use biofuels, by-products rich in protein or energy used for feed and aquatic products.

Animal products are translated into virtual land based on EU feed regimes.

Data

All data is taken from CAPRI.

Calculation

Oilseeds

Yields per hectare of processed products, oilseed cake and oil, are weighted based on their output shares in oilseed processing.

Composition of feed concentrates

The CAPRI Graphical User Interface does not specify the quantitative composition of feed concentrates. The yields for feed concentrates are calculated based on the yields of the individual components, weighted by their total feed use. Components that are not cropped to be used as feed (e.g., side-streams from vegetable production) are not considered. The feed composition is as follows:

- Feed cereals: barley, grain maize, oats, other cereals, milled rice, rye and meslin,
- Feed rich protein: pulses, rapeseed cake, rapeseed oil, soya cake, soya oil, sunflower seed cake and sunflower seed oil,
- Other feed: rapeseed, soya seed and sunflower seed.

For the concentrate category "Feed rich energy", we calculate the yield per hectare to be the average of rapeseed oil and sugar from sugar beet.

The CAPRI model does not provide data on feed regimes outside of the EU. Consequently, we estimate the fodder area requirement for animal products using EU feed regimes and world average yields. Due to a lack of data on fodder yields outside the EU, we estimate fodder yields outside the EU using EU fodder yields and the yield ratios between EU and world averages for proxy plants. The proxy plants are:

- Grain maize: as a proxy for "fodder maize",
- Potatoes: as a proxy for "fodder root crops",
- Barley: as a proxy for "grass" and "fodder other on arable land".

Land requirement of animal products

The virtual land requirement for animal products is calculated based on the fodder used at every stage of animal production. We use the categories for animal products as outlined by the CAPRI Graphical User Interface:

- Beef: heifers fattening high weight, heifers fattening low weight, male adult cattle high weight, male adult cattle low weight and other cows,
- Dairy: dairy cows high yield, dairy cows low yield, heifers breeding, raising male calves, raising female calves, fattening male calves, fattening female calves, milk ewes and goats,
- Pig meat: pig breeding and pig fattening.

The other animal products have only one attributed CAPRI category. For the conversion of milk products into milk equivalents, see Annex Chapter 5.

Results

Table A4 shows the virtual land trade balances for 2020 and 2045. In addition to the virtual land trade balance for the 2045 main scenario, the virtual land trade balance is also calculated for a 2045 sensitivity analysis, in which dietary patterns remain unchanged.

Virtual land trade of the EU in 2020 and 2045

→ Table A4

Scenario	Product category	Virtual land import (million ha)	Virtual land export (million ha)	Net virtual land trade (million ha)
2020	**Livestock products**	–2	17	15
2045 scenario without dietary change	Livestock products	–3	11	7
2045 main scenario	Livestock products	–1	33	32
2020	**Plant products**	–40	23	–16
2045 scenario without dietary change	Plant products	–37	15	–22
2045 main scenario	Plant products	–32	20	–11
2020	**Total**	–42	41	–1
2045 scenario without dietary change	Total	–40	26	–14
2045 main scenario	Total	–33	54	21

3 Biomass (Chapter 4.2)

3.1 Biomass supply and demand

The aim of this calculation is to project a closed balance for demand and supply of solid biomass for material and energy use in 2045 and, as part of the balance, to determine the supply of lignocellulosic biomass needed from agricultural land. For biogas and biomethane, no explicit calculation for biomass supply is conducted.

Short method description

We derive the demand for biomass in 2045 from two external studies. For material use, we draw on the "high-value scenario" by Material Economics (2021). The bioenergy demand comes from the Agora Energiewende scenario "Breaking free from fossil gas" (Agora Energiewende 2023).

To match supply with demand, we follow a two-step approach:
1. We make assumptions or calculate the supply of biomass from forests, paludiculture and waste.
2. We complement this supply with lignocellulosic biomass from agricultural land to close the balance.

Data and calculation

Based on the studies mentioned above, the total use of biomass in the EU-27 increases by around one-fifth, from about 2 400 terawatt-hours (TWh) in 2020 to approximately 2 900 TWh in 2045. This total for 2045 breaks down into around 1 200 TWh for energy use and around 1 700 TWh for material use. Solid biomass demand is around 2 700 TWh, while around 200 TWh is biogas or biomethane. Liquid biofuels are derived from solid biomass, around 60 TWh for advanced biofuels and 220 TWh for synthetic fuels (Agora Energiewende 2023). First-generation liquid biofuels are assumed to be largely phased out, although fuels for offroad vehicles, such as farm machinery, could be partly produced from vegetable oils. This possibility is not explicitly calculated.

For the forest biomass, we convert the harvest given in cubic meters (Annex Chapter 8.2) into tonnes, using a conversion factor of 2.25 cubic meters per tonne of dry matter for coniferous trees and 1.60 cubic meters per tonne of dry matter for non-coniferous trees. We apply an energy content of 5 megawatt-hours (MWh) per tonne of dry matter (Material Economics 2021).

For the biomass from fast-growing trees, we assume a yield of 10.2 tonnes of dry matter per hectare and year and a lower heating value for the harvested wood of 15.4 megajoule per kg (for wood with 15% moisture content) (FNR 2014). We assume that part of the wood will be dried with external energy, so that the resulting moisture content is 24% on average when the wood is burned and dry matter losses through respiration in the passive drying process can be limited to 9%. This results in 4 475 kilowatt-hours (kWh) per tonne of dry matter, or around 45 650 kWh per hectare and year.

For paludiculture, the production is calculated with a conservative yield between 3.5 and 8.2 tonnes of dry matter per hectare and year and an energy content of 5 MWh per tonne of dry matter (Dahms et al. 2017, Närmann et al. 2021, Nordt et al. 2022).

Results

The total demand for solid biomass (2 700 TWh) in 2045 is divided into 1 000 TWh for energy use and 1 700 TWh for material use. This total demand, which we expect to be mainly in the form of woody biomass, is first met with:

- 1 130 TWh from the harvest from European forests, which is reduced by 10% and to which we add the net import of round wood frozen at the 2020 level around (30 TWh).
- 410 TWh from the co-products of the forest harvest, (reduced also by 10%), and about 280 TWh to take unreported sources of woody biomass into account (European Commission 2021).
- 40 TWh from the paludiculture biomass produced on 80% of the rewetted peatlands (2.2 million hectares).
- 150 and 70 TWh respectively from paper and wood waste, which are assumed to be stable between 2020 and 2045.

The 580 TWh gap between demand and production of woody biomass is filled by the production of fast-growing trees on 12.7 million hectares of agricultural land.

3.2 Establishment of fast-growing trees on agricultural land

In our scenario, fast-growing trees are established on 12.7 million hectares by 2045. The geographical distribution of these trees across the NUTS-2 regions is described here. The aim of the spatial allocation is to derive explicit area needs for each region to reach consistency with the CAPRI modelling of land use for other crops.

Short method description

To take into account the area for fast-growing trees in the agricultural land balance, an area for these trees is reserved for each NUTS-2 region. This reserved area is not subject to the optimisation process through the CAPRI modelling. Tree cover and precipitation per region as well as overall availability of agricultural land projected to be fallowed by the CAPRI modelling are taken into account.

Data

Data on tree cover (forest plus fast-growing trees) are derived from the CAPRI land balance; data on precipitation are derived from von Behr et al. (2012).

Calculation and results

We allocate the area of fast-growing trees at the level of NUTS-2 regions in the EU as follows:

1. 30 NUTS-2 regions where the average precipitation is expected to be below 300 mm in the growing period (spring and summer) according to von Behr et al. (2012) are excluded, as they cannot provide the minimum water requirements of fast-growing trees.
2. The allocation process ensures that the maximum tree cover (forests plus fast-growing trees) does not exceed 50% of the land area. By doing this, we avoid creating new woody biomass resources where forests are abundant and prevent an excessive concentration of tree cover which potentially threatens species that rely on open landscapes as habitat (Finck et al. 2002). This leads to 32 regions being fully excluded from the allocation of fast-growing trees, while in many others it leads to an underproportional area share of trees on agricultural land.
3. An area of 0.7 million hectares of fast-growing trees on grassland is allocated proportionally to the area of grassland in each region, provided that regional tree cover stays below 50% and there is enough precipitation.
4. An area of 12 million hectares of fast-growing trees on arable land is allocated respecting the aforementioned constraints as follows:

- Up to 50% of the area required for productive semi-natural landscape features are devoted to fast-growing trees. In total, this results in 1.3 million hectares.
- Up to 30% of the land not allocated to other crops by the CAPRI model (CAPRI land category "FALLOW") are devoted to fast-growing trees. In total, this results in 0.7 million hectares.
- The remaining 10 million hectares are allocated proportionally to arable land endowment across the NUTS-2 regions.

Except for a few technical outliers, as a result of this allocation process, between 0 and 18% of the agricultural area are allocated to fast-growing trees across NUTS-2 regions, with an average value of 8%.

3.3 Net CO_2 removals from the establishment of fast-growing trees

The aim of this calculation is to determine the net carbon dioxide (CO_2) removals from the establishment of fast-growing trees on agricultural land as assumed in our scenario. Therefore, we calculate:

- The net sequestration per hectare for the establishment of fast-growing trees with a harvest cycle length of seven years (exemplary calculation).
- The overall carbon balance of the establishment of fast-growing trees according to our scenario for the period 2025–2045.

To calculate the overall balance for the period 2025–2045, we assume that the area of fast-growing trees increases linearly between 2025 and 2045, reaching 12 million hectares on arable land and 0.7 million hectares on grassland by 2045. No fast-growing trees are established on organic soils. Areas for fast-growing trees are introduced exogenously into the land balance of CAPRI to ensure the consistency of our scenario regarding land use (Annex Chapter 2.3).

We find potential average CO_2 removals by fast-growing trees for the deployment period 2025–2045 of about 30 Mt per year. After 2045, the annual sequestration potential starts to decrease and reaches 0 within a few years.

Short method description

Additional sequestration from fast-growing trees is calculated by multiplying the fast-growing tree area with the emission factors for the aboveground and belowground biomass and by factoring in land-use change effects.

The linear phase-in implies an additional area of fast-growing trees of 0.57 million hectares per year. Based on this path, we calculate the annual carbon balance assuming a production cycle of 7 years. Every seven years, the aboveground biomass is fully harvested. The belowground biomass is assumed to grow linearly for the first seven years and stay constant afterwards. This is in line with the approach used in the German Greenhouse Gas (GHG) inventory (Umweltbundesamt 2023).

Data and assumptions

The emission factors for the aboveground and belowground biomass are derived from the yield of dry matter per hectare of fast-growing trees, which is assumed to be 10.2 tonnes per year based on FNR (2014). A carbon fraction of 50% is assumed for the dry biomass.

To include the land-use change effect from annual crops and grassland to fast-growing trees, we also use the emission factors from Umweltbundesamt (2023).

Following Wüstemann et al. (2023), we assume no change in soil carbon after land-use change from arable land to fast-growing trees, while other sources suggest an increase (Baum et al. 2009). The decrease of soil carbon stocks after land-use change from grassland to fast-growing trees is calculated by subtracting the soil carbon stock of grasslands from the soil carbon stock under fast-growing trees using figures from Umweltbundesamt (2023).

Calculation

The CO_2 sequestration per hectare and year in the aboveground biomass is calculated by multiplying the assumed dry matter yield with a carbon fraction of 50%. For the belowground biomass, a root-to-shoot factor of 19.2% from guidelines of the Intergovernmental Panel on Climate Change (IPCC) is applied (IPCC 2019).

For the first year after land-use change, we calculate the balance of carbon in biomass with the gain-loss method according to the IPPC (Bickel et al. 2006), subtracting the biomass of the annual crop from the biomass of the trees after one year of growth. We also account for a one-time loss of soil carbon of 25.2 tonnes per hectare for grassland.

For the exemplary calculation of CO_2 sequestration per hectare, our reasoning is as follows: after fast-growing trees have been established, the amount of carbon in aboveground biomass fluctuates between zero at the beginning and right after harvest and the amount accumulated right before harvest (7 years after planting). We assume, therefore, that the stock accumulated after half of the harvest cycle (3.5 years) most accurately reflects the average carbon bound in aboveground biomass. For belowground biomass, we assume that the amount of carbon bound after one harvest cycle (7 years) most accurately reflects the average carbon stock.

Results

The results are shown in Table A5. The first two columns show the result of the exemplary calculation, while columns 3 and 4 show the overall CO_2 balance of our scenario during the period 2025 to 2045. The last two columns break down these values into an annual average.

Average CO_2 sequestration gains from fast-growing trees established on former arable land and grassland

→ Table A5

	Net sequestration per hectare (exemplary calculation) (tonnes CO_2)		Total net sequestration 2025-2045 ($MtCO_2$)		Average net sequestration per year 2025–2045 ($MtCO_2$)	
	Arable land (1 ha)	Grassland (1 ha)	Arable land (12 million ha)	Grassland (0.7 million ha)	Arable land (12 million ha)	Grassland (0.7 million ha)
Aboveground biomass	47.5*	51.6*	457.6	29.6	21.8	1.4
Belowground biomass	19.0	14.0	184.6	7.3	8.8	0.3
Soil	0	−25.2**	0	−17.6	0	−0.8
Total	66.5	40.4	642.2	19.2	30.6	1.1

* Corresponds to the 3.5-year stock minus the carbon stock of annual crops,
** One-time loss of carbon in the year of establishment

3.4 Impact of fast-growing trees on the use of nitrogen fertilisers and plant protection products

We assume that fast-growing trees are grown without the use of nitrogen fertiliser and plant protection products. Therefore, allocating agricultural land to fast-growing trees contributes to the overall reduction of these inputs. In our scenario, we achieve an overall 31% reduction in the total amount of nitrogen fertilisers (i.e., synthetic fertilisers, manure and other sources), while the use of plant protection products decreases by 52%.

Short method description

We calculate how much the fast-growing trees in our scenario contribute to the reduction of the area on which plant protection products and nitrogen inputs are used. By comparing this to the overall agricultural area, we calculate a theoretical contribution of this fast-growing tree area expansion to the reduction in inputs under the assumption that input intensity is unchanged on all other agricultural land. By then comparing this theoretical reduction to the achieved reduction in our scenario, we estimate the relative contribution of fast-growing trees to the total input reduction.

Data

Data on land areas and amounts of managed nitrogen comes from CAPRI modelling. Data on the reduction of plant protection products is based on CAPRI results. In our 2045 scenario, the use of plant protection products is reduced by 52% compared to 2020. CAPRI results indicate a reduction by 37%, while we assume that technical innovations in plant protection, plant breeding and diversification of cropping systems could save another 15% of plant protection products applied without loss of yield (Annex Chapter 6.5).

Calculation

The calculation is carried out as follows:

$$Contribution(FGT)_i = -\frac{Area(FGT, 2045)}{AgArea(2020) * \ Reduction(2020 - 2045)_i}$$

where $Contribution(FGT)_i$ is the theoretical relative contribution of planting fast-growing trees (FGT) in our scenario to the reduction of input i, $Area(FGT, 2045)$ is the area of fast-growing trees in our scenario, $AgArea(2020)$ is the agricultural area in 2020 and $Reduction(2020 - 2045)_i$ is the reduction of input i achieved with our scenario compared to 2020.

Results

The results are depicted in Table A6.

Theoretical contribution of fast-growing trees to input reduction → Table A6

Headline	Area (FGT, 2045) (million ha)	AgArea (2020) (million ha)	Reduction 2020-2045 (%)	Theoretical contribution of fast-growing trees (percentage points)	Theoretical contribution of fast-growing trees (% of 2020–2045 reduction)
	(1)	(2)	(3)	(4) = (1)/(2)	(5) = (4)/(3)
Nitrogen fertiliser	12.7	161.8	–30.8	–7.9	25.5
Plant protection products			–52.0		15.1

3.5 Sensitivity analysis (scenario without fast-growing trees)

As a sensitivity analysis, a scenario with the full scenario implementation except the implementation of fast-growing trees on agricultural land aims at assessing the isolated effect of allocating 12.7 million hectares to fast-growing trees by 2045 on:

- The GHG balance of EU agriculture and the impact on agricultural GHG emissions in the rest of the world,
- Agricultural production and trade balances.

These results also give an indication of the order of magnitude of the effect of fast-growing trees on the EU virtual land trade balance.

Short method description

A scenario with the same parameters as our main scenario but without allocating any agricultural land to fast-growing trees is run in CAPRI.

Data

Data is taken from CAPRI modelling results.

Calculation and Results

For GHG emissions, agricultural production and trade balance figures, CAPRI results for the main scenario and the scenario without fast-growing trees are directly compared. Selected results are shown in Table A7.

Crop production, trade and agricultural emissions with and without fast-growing trees → Table A7

	Main scenario 2045	Scenario without fast-growing trees 2045	Difference between scenario without and with fast-growing trees
Net production (Mt)			
Cereals	172.1	190.1	18.0
Oilseeds	32.3	34.4	2.1
Other arable field crops	38.9	39.7	0.9
Vegetables and permanent crops	162.2	161.3	–1.0
Net trade (Mt)			
Cereals	18.0	30.1	12.0
Oilseeds	–15.4	–12.9	2.5
Other arable field crops	–8.0	–7.3	0.7
Vegetables and permanent crops	–16.4	–16.9	–0.5
GHG emissions (MtCO$_2$eq)[1]			
Agricultural GHG emissions in the EU-27	187.4	196.7	9.3
Agricultural GHG emissions in the rest of the world	6226.0	6221.9	–4.2

1) Original CAPRI results without calibration

4 Food demand (Chapter 4.3)

4.1 Food consumption, intake and nutrient content

Food consumption in CAPRI is derived at the country level based on food availability data from FAOSTAT (2024) and Eurostat (CAPRI model documentation 2022). The 2020 calorie intake is calculated by adjusting consumer demand for country- and product-specific food waste at the household level and food loss at the distribution level, based on Food and Agriculture Organization (FAO) values (Gustavsson et al. 2011). Food waste and loss shares are further adjusted to align to food calorie requirements in line with findings from Rieger et al. (2023), while adding 2020 consumption levels for beer, wine and cacao. This results in an EU intake baseline of 2418 kilocalories (kcal) for 2020.

The nutrient contents per kilogram of food products, including energy content (kcal), protein and fat, are derived from the United States Department of Agriculture food database (USDA 2024). These data are used universally across all countries and regions to convert the food products demanded by consumers within the CAPRI model into their respective nutrient profiles (Table A8).

Nutrient content per kg of food product in CAPRI → Table A8

Food products	Energy content (kcal/kg)	Protein content (g/kg)	Fat content (g/kg)
Wheat	3 400	107	20
Rye and meslin	3 380	103	16
Barley non-beer	3 540	125	23
Oats	3 890	169	69
Grain maize	3 650	94	47
Other cereals	3 360	123	30
Rice milled	3 645	66	21
Sunflower seeds	5 840	208	515
Soya seeds	4 460	365	199
Pulses	3 143	226	31
Potatoes	770	20	1
Tomatoes	180	9	2
Other vegetables	293	9	1
Apples, pear and peaches	493	5	2
Citrus fruits	490	9	2
Table grapes	630	8	3
Other fruits	683	8	3
Table olives	1 150	8	107
Beef	2 188	134	179

Pig meat	2 892	107	270
Sheep and goat meat	2 188	134	179
Poultry meat	1 708	142	123
Eggs	1 430	126	95
Freshwater fish	1 115	190	37
Saltwater fish	1 447	205	63
Other aquatic	752	135	12
Whey powder	3 460	123	8
Whole milk powder	4 960	263	267
Butter	7 170	9	811
Skimmed milk powder	3 620	362	8
Cheese	3 338	215	267
Fresh milk products	610	42	24
Cream	1 950	27	193
Concentrated milk	3 210	79	87
Raw milk	615	32	33
Rapeseed oil	8 840	0	1 000
Sunflower seed oil	8 840	0	1 000
Soya oil	8 840	0	1 000
Olive oil	8 840	0	1 000
Palm oil	8 730	0	1 000
Other oil	8 840	0	1 000
Cocoa	2 280	196	137
Sugar	3 835	1	
Wine	830	1	

Agora Agriculture based on CAPRI results

4.2 Calorie intake per person per day by 2045

We calculate an average calorie intake of 2 140 kcal/capita/day in the EU in 2045 based on Eurostat population projections (Eurostat 2023f) and Dietary Reference Values for energy provided by the European Food Safety Authority (EFSA 2013).

Dietary energy needs

We assume a Physical Activity Level of 1.6, which according to EFSA (2013) reflects moderate physical activity in adults. Given that today's average physical activity levels are lower, this translates into a slight increase in activity.

We assume a body mass index (BMI) of 22 kg/m², representing the midpoint of the healthy BMI range for adults (EFSA 2017). Currently, more than 50% of the EU population has a BMI over 25 and 15% of the EU population has a BMI above 30 (Eurostat 2019).

Population

We use Eurostat baseline population projections for 2045 (Eurostat 2023f). Birth projections for 2045 are used to reflect the calorie needs of pregnant and breastfeeding women.

Method

We match the EFSA's average energy requirements in kcal/day, specified for different sexes, ages, and for pregnant and breastfeeding women, with the projected 2045 population in each segment to calculate average energy needs per capita (EFSA 2013, Eurostat 2023f).

4.3 Consumption patterns in 2045

We calculate a weighted average for 2045 consumption patterns by assigning an 80% weight to the reference values of the Planetary Health Diet (PHD) (Willett et al. 2019) and the accompanying calculations to the PHD as published by Springmann et al. (2018) The 2020 consumption patterns for all product groups in each EU member state are weighted by 20%. Some exceptions are made for certain food groups, as the classifications in the PHD and CAPRI differ slightly, requiring adjustments (Table A9). To validate that the results align with other dietary guidelines promoting healthy diets with reduced environmental impacts, we compare them with selected studies (including Blomhoff et al. 2023, European Commission 2023, Ministry of Food, Agriculture and Fisheries of Denmark 2021, Schäfer et al. 2024, WHO European Region 2023).

Adjustments related to the Planetary Health Diet

We use the "Planetary Health Diet" as a reference for the intake for different food groups. In our scenario, the daily average requirement is adapted to 2 140 kcal per day per person. The difference between 2 500 kcal as referred to in Willet et al. (2019) and 2 140 kcal in our model is adjusted by reducing the intake of staple foods.

The resulting food intake in 2045 is used to shift human-demand functions in CAPRI. Adjustments are made where necessary to account for differences in food group classifications between CAPRI and the PHD (Table A9). Final CAPRI results deviate slightly from the model input in Table A9, as additional changes result in CAPRI from changes in market equilibrium prices.

Kilocalorie requirements per food group in the Planetary Health Diet and the 2045 scenario

→ Table A9

Planetary Health Diet (Willett et al. 2019) based on 2 500 kcal			Scenario 2045 (Input-CAPRI) based on 2 140 kcal	
Food group	Food subgroups	(kcal/day)	Food subgroups examples	(kcal/day)
Whole grains	Rice, wheat, corn, others	811	Cereals (wheat, rye and meslin, barley, oats, grain maize, other cereals, rice)	519
Tubers/starchy vegetables	Potatoes, cassava	39	Potatoes	58
Vegetables	Dark green, red, orange and other vegetables	78	Tomatoes, other vegetables	78
Fruits	All fruits	126	Apples, citrus fruits, table grapes, table olives, other fruits	123
Dairy foods	Whole milk or derivative equivalents (e.g., cheese)	153	Whey powder, casein, whole milk powder, butter, skimmed milk powder, cheese, fresh milk products, cream, concentrated milk, raw milk	205
Protein sources	Beef and lamb	15	Beef	22
			Lamb	3
	Pig meat	15	Pig meat, lard, tallow	76
	Poultry meat	62	Poultry meat	65
	Eggs	19	Eggs	23
	Fish	40	Fresh water fish, salt water fish, other aquatic products	45
	Pulses (beans, peas)	172	Pulses kcal for nuts included	171
	Soya	112	Soya kcal for peanuts and nuts included	179
	Peanuts	142	Included in soya	
	Tree nuts	149	Included in soya and pulses	
Added fats	Unsaturated oils (e.g., olive, rapeseed oil)	354	Vegetable oils (rapeseed, sunflower, soya, olive, other oils)	383
	Palm oil	60	Palm oil	43
	Lard/tallow	36	Included in pig meat	
Added sugars	All sweeteners	120	Sugar	149
Total		**2 503**		2 140

Agora Agriculture based on CAPRI results and Willet et al. (2019)

Unlike the PHD, we include cacao and a moderate consumption of alcohol in our dietary patterns. CAPRI provides data for wine, barley (for non-alcohol and alcohol products) and for cacao. CAPRI does not provide data for coffee, tea and spirits. To account for energy intake from these categories, we assume an additional intake:

- 94 kcal from alcohol (wine, beer, spirits) in 2045, representing a 29% decrease compared to 2019 levels.
- 12 kcal from cacao, maintaining 2020 consumption levels.

4.4 Assumptions on food losses and food waste

CAPRI contains data on food losses and waste in two categories: "Losses at consumption stage" and "Market losses". While losses at consumption stage include food waste from the retail sector up to private households, market losses include losses from agriculture and processing. The high amounts of food loss and waste in CAPRI are not directly comparable to the amounts officially reported by EU member states (Eurostat 2023b) and calculations by Joint Research Center (De Laurentiis et al. 2023).

In our scenario, halving food waste is applied by halving rates of "losses at consumption stage" based on the 2045 consumption patterns. Since the 2045 diets include more perishable products (i.e., fruit and vegetables), which have high loss and waste rates, the absolute amount of waste increases. Therefore, halving losses at consumption stage in 2045, compared to 2020, results in a 40% reduction in absolute quantity (total weight, without differentiating between edible and inedible waste).

In our scenario, we do not assume any reduction in market loss rates. As a result, absolute "market losses" for some food categories, particularly fruits and vegetables, increase due to higher consumption levels.

4.5 Sensitivity analysis

The sensitivity analysis illustrates the isolated effect of dietary changes and food waste reduction. It assumes no shifts in demand functions and no reductions in food loss and waste.

5 Livestock farming (Chapter 4.4)

5.1 CAPRI model inputs

For our 2045 scenario, specific CAPRI parameters are adjusted compared to the standard baseline for that year (Annex Chapter 1) to reflect changing agricultural practices:

Milk yields

We adjust region-specific milk yields on the NUTS-2 level, assuming improved breeding methods and a higher proportion of forage from grassland in the feed composition. In regions where milk yields are lower than the EU average in 2020 (7 159 litres per cow per year), we assume milk yields to increase due to improved breeding methods. In highly productive regions, we assume yields to decline due to the shift to more grassland-based feeding.

Shifts in supply function for eggs, poultry and pig meat

In our 2045 scenario, EU demand for eggs, poultry and pig meat declines, while animal welfare standards increase. To address the additional costs associated with meeting these higher animal welfare standards, we propose compensating them through public animal welfare payments. However, these increased costs for animal welfare and compensatory payments are not technically included in the CAPRI scenario. Essentially, the costs for welfare improvements are anticipated to be offset by the compensatory payments, resulting in minimal economic impact on farms. As we consider it unlikely that EU taxpayers would be willing to fund animal welfare costs for large export quantities, we shift supply functions leftward by about 13 to 20% for these products. This adjustment ensures that net exports do not increase significantly.

Grass content in forage

The proportion of grass from permanent grassland in forage (calculated as dry matter) is regionally adjusted in the diet of dairy cows, breeding heifers and suckler cows. The NUTS-2 regions are divided into three classes based on grass content in forage:
- Regions with less than 45% grass in forage: the grass share increases by 35% points,
- Regions with 45–80% grass in forage: the grass share increases by 22% points,
- Regions exceeding 80% grass in forage: no adjustment to the grass share is made.

We recognize that assuming an average milk yield of 7 700 litres in 2045 with a predominately grassland-based feed ration is ambitious.

Milk equivalents

Dairy products (Eurostat 2023a) are converted into milk equivalents for comparison across all dairy-product categories. This conversion is based on the combined fat and protein content. Table A10 shows the conversion factors for all CAPRI milk products for the year 2020 and the 2045 scenario. The conversion factors are used to calculate market balances of dairy products in milk equivalents (Figure 22: EU cattle densities and market balances for dairy products in 2020 and 2045).

Milk equivalents conversion factors → Table A9

Dairy product category	Base year 2020	2045 scenario
Butter	10.02	10.11
Casein	11.41	11.81
Cheese	6.18	6.47
Concentrated milk	1.88	1.88
Cream	3.49	3.50
Fresh milk products	0.82	0.80
Skimmed milk powder	4.23	4.28
Whey powder	1.50	1.55
Whole milk powder	7.51	7.88

5.2 Livestock density (Figures 20–23)

We aggregate the main livestock species in 2020 and 2045 into livestock units (LSU). The LSU is a conversion ratio based on metabolizable energy requirements for each livestock species, with one unit representing the maintenance and production needs of a typical dairy cow.

The calculations are based on herd sizes for 2020 and 2045 from CAPRI. Table A11 shows the LSU conversion coefficients for each livestock species (Eurostat 2023e). The CAPRI model disaggregates cattle into dairy cows, bulls, heifers, suckler cows and calves. Poultry fattening and pig fattening are expressed by the CAPRI model as slaughtered animals per year. Further details on the conversion process for each farm animal category are provided below.

CAPRI livestock unit coefficients

→ Table A11

Farm animal	Category	Livestock unit coefficient
Cattle	Dairy cows	1.0
Cattle	Male adult cattle low weight	0.7
Cattle	Male adult cattle high weight	1.0
Cattle	Heifers fattening low weight	0.7
Cattle	Heifers fattening high weight	0.8
Cattle	Other cows	0.8
Cattle	Heifers breeding	0.7
Cattle	Fattening calves	0.4
Cattle	Raising calves	0.4
Sheep and goats	Sheep and goats	0.1
Pigs	Pig breeding (sows)	0.77
Pigs	Pig fattening	0.3
Poultry	Poultry fattening	0.007

Figure 20: EU livestock densities and meat market balances in 2020 and 2045

Per NUTS-2 region, the numbers of individual cattle types, poultry, pig, ewes and goats for milking, sheep, and goat fattening are multiplied by their LSU coefficient, resulting in the total LSU per NUTS-2 region. This number is then divided by the Utilised Agricultural Area (UAA) of the respective NUTS-2 region, resulting in the LSU density on the NUTS-2 level.

Figure 21: EU pig densities in 2020 and 2045

For the calculation of pig density per NUTS-2 region we:

1. Convert the "pig fattening aggregate", which is expressed in animals fattened per year to herd size. This aggregate includes "pigs with a live weight of 20 kg and less than 50 kg" and "fattening pigs (including discarded boars and sows) with a weight of at least 50 kg". This is done by dividing the pig aggregate by the number of average national production cycles per year. The result is multiplied by the pig LSU coefficient and divided by the corresponding UAA of the NUTS-2 region.
2. Use the "sows" aggregate, which is given as herd size. The herd size is multiplied by the sow LSU coefficient (0.77), which includes not only sows but also piglets. The result is divided by the corresponding UAA of the NUTS-2 region.
3. Sum up the LSU from the pig aggregate and the LSU of the sows.

Figure 22: EU cattle densities and market balances for dairy products in 2020 and 2045

Cattle density includes both dairy and beef cattle categories, which are converted into LSU units per UAA at the NUTS-2 level.

Figure 23: EU poultry densities and market balances for eggs in 2020 and 2045

The LSU conversion for poultry fattening includes poultry species, ducks, geese, turkeys and broilers. This aggregate is expressed in animals fattened per year and is converted to herd size. This is done by dividing the poultry aggregate by the number of average national production cycles per year. The result is divided by the corresponding UAA of the NUTS-2 region.

5.3 Mitigation technologies (Chapter 4.4.1 Section B)

This section provides an overview of 10 mitigation technologies aimed at reducing greenhouse gas (GHG) emissions in the livestock sector, particularly for methane (CH_4) and nitrous oxide (N_2O). While some of these technologies are explicitly modelled in CAPRI, others are not. We estimate the quantitative mitigation potential of modelled technologies based on adoption rates listed in Tables A12, A13 and A14.

CAPRI mitigation technologies

The CAPRI model assumptions for each of the six mitigation technologies (anaerobic digestion, nitrate feeding, linseed-oil feeding, low-protein feeding, anti-methanogen vaccination and breeding for ruminant efficiency) are based on Pérez Domínguez et al (2020).

Additional mitigation technologies

We assume that each of the selected four technologies which are not modelled in CAPRI (methane inhibitor, manure additives, slurry removal/cooling and nitrification inhibitor) achieve an optimistic adoption rate of 50% by 2045. Combined with the technologies integrated in the CAPRI model, this gives a total mitigation potential of 37 million tonnes of carbon dioxide equivalent ($MtCO_2eq$) compared to 2020. The uptake of these technologies depends on various factors, including their application costs, their future development, usability and the changes in animal husbandry systems. We calculate a less ambitious potential of 26 $MtCO_2eq$ with a 25% adoption rate and a highly ambitious potential of 47 $MtCO_2eq$ with a 75% adoption rate for the additional technologies. Additional mitigation technologies are assumed to have an adoption rate of 0% in 2020. In reality, there may be emissions reductions, but these are likely marginal, amounting to less than 1% for each technology (Herrero et al. 2015: 29).

CAPRI and additional mitigation technologies for livestock are described below in order from highest to lowest mitigation potential. The share of emission savings for each technology is given in million tonnes of CO_2eq ($MtCO_2eq$) and as a percentage of total technological emission savings. The average emission reduction is based on input data from CAPRI or on the literature.

Methane inhibitor (3-nitrooxypropanol, feed additive)

- Target greenhouse gas: Methane
- Description: This feed additive acts as a methane inhibitor in the rumen, disrupting specific enzymes involved in methane production by methanogenic archaea. It effectively reduces methane emissions without compromising animal productivity or health.
- Total emissions savings 2020: 0 $MtCO_2eq$
- Total emissions savings 2045: 9.23 $MtCO_2eq$ (25.31%)
- Average methane reduction: 32.7%
- Source: Kebreab et al. (2023)

Anaerobic digestion

- Target greenhouse gases: Carbon dioxide, methane, nitrous oxide
- Description: Microorganisms break down biodegradable material in the absence of oxygen. Anaerobic digestion can take place on farms to produce biogas from animal waste. Biogas comprises methane and carbon dioxide and serves as a renewable energy source. More details about our assumptions on anaerobic digestion can be found in Chapter 4.5.
- Total emissions savings 2020: 1.02 $MtCO_2eq$
- Total emissions savings 2045: 8.47 $MtCO_2eq$ (23.22%)
- Assumptions: Only farms with more than 200 livestock units use anaerobic digestion as an economically viable option to mitigate emissions from manure. Adoption of anaerobic digestion is assumed not to be profitable for farms with less than 200 livestock units.
- Average emissions reduction: Incalculable due to indirect greenhouse gas savings from renewable energy adoption over fossil fuels, as well as variability in factors such as manure input quantities and digestate application methods.
- Source: CAPRI, Pérez Domínguez et al. (2020)

Manure additives (acidification)

- Target greenhouse gas: Methane
- Description: Acidification lowers the pH of slurry, suppressing microbial activity and mitigating methane (CH4) and ammonia (NH3) emissions from pig and cattle slurry. The potential indirect greenhouse gas effect of NH3 is not accounted for in our calculation.
- Total emissions savings 2020: none
- Total emissions savings 2045: 7.08 MtCO2eq (19.41%)
- Average emissions reductions: 88.4% CH4, 64.5% NH3
- Source: Ambrose et al. (2023), Herrero et al. (2015), Holtkamp et al. (2023)

Slurry removal/cooling

- Target greenhouse gas: Methane
- Description: These systems efficiently extract residual waste, facilitate rapid cooling and ensure secure storage for both cattle and pig slurry, minimizing CH4 production.
- Total emissions savings 2020: none
- Total emissions savings 2045: 3.40 MtCO2eq (9.31%)
- Average methane reduction: 52.7%
- Source: Ambrose et al. (2023), Dalby et al. (2023), Hilhorst et al. (2002), Ibidhi & Calsamiglia (2020), Ngwabie et al. (2016)

Nitrate (feed additive)

- Target greenhouse gas: Methane
- Description: Nitrate acts as an alternative hydrogen sink in the rumen, reducing methane production. Nitrate feeding has been applied in various proportions to dairy cows and fattening cattle, with intake limitations to ensure safety.
- Total emissions savings 2020: 0.004 MtCO2eq
- Total emissions savings 2045: 2.73 MtCO2eq (7.48%)
- Assumptions: Applied to 100% of dairy cows and to 50% of fattening cattle and replacement heifers. Intake of nitrate is limited to a maximum of 1.5% of total dry matter intake.
- Average methane reduction: 15.0%
- Source: CAPRI, Pérez Domínguez et al. (2020)

Linseed oil (feed additive)

- Target greenhouse gas: Methane
- Description: Omega-3 fatty acids in linseed suppress methane formation in the rumen. They are used in dairy cattle herds and other cattle categories with controlled intake levels.
- Total emissions savings 2020: 0.004 MtCO2eq
- Total emissions savings 2045: 2.39 MtCO2eq (6.54%)
- Assumptions: Applied to 100% of the dairy cattle herd, but to only 50% of other cattle categories, as the intake must be constant and can be better controlled for dairy cows. Feeding of linseed is limited to a maximum of 5% of total fat in dry matter intake.
- Average methane reduction: 25.0%
- Source: CAPRI, Pérez Domínguez et al. (2020)

Nitrification inhibitor (dicyandiamide, slurry additive)

- Target greenhouse gas: Nitrous oxide
- Description: Nitrification inhibitors slow down the conversion of ammonium to nitrate by inhibiting specific enzymes in nitrifying bacteria. This reduction in nitrate formation helps mitigate the release of nitrous oxide. Applied to pig slurry, cattle slurry/urine and dairy cow feed.
- Total emissions savings 2020: none
- Total emissions savings 2045: 1.18 MtCO2eq (3.23%)
- Average nitrous oxide reduction: 65.9%
- Source: Cahalan et al. (2015), Luo et al. (2015), Minet et al. (2016), Simon et al. (2020), Suleiman et al. (2016)

Anti-methanogen vaccination

- Target greenhouse gas: Methane
- Description: Methanogens in the rumen produce methane as a by-product. The vaccine stimulates the animal's immune system to produce antibodies against methanogens, reducing CH4 emissions.
- Total emissions savings 2020: none
- Total emissions savings 2045: 0.98 MtCO2eq (2.69%)
- Assumptions: Based on data from the model GAINS (GHG and Air Pollution Interactions and Synergies), Pérez Domínguez et al. (2020), methane emissions from enteric fermentation are reduced for dairy, non-dairy cattle and sheep by 5%. Cost: 10 euro per animal per year.
- Average methane reduction: 5.0%
- Source: CAPRI, Pérez Domínguez et al. (2020)

Breeding for ruminant feed efficiency

- Target greenhouse gas: Methane
- Description: Genetic variations in feed efficiency influence methane production. More efficient animals require less feed intake, resulting in fewer fermentative processes in the rumen and reduced methane emissions.
- Total emissions savings 2020: none
- Total emissions savings 2045: 0.95 MtCO2eq (2.60%)
- Assumptions: 10% reduction in energy need of non-dairy ruminants; crude protein needs decline by 5% for all ruminants
- Average methane reduction: 10.0%
- Source: CAPRI, Pérez Domínguez et al. (2020)

Low-protein feeding

- Target greenhouse gas: Nitrous oxide
- Description: Excess protein intake leads to the excretion of nitrogen primarily as urea, which can contribute to the formation of nitrous oxide (N2O) and ammonia (NH3). By reducing crude protein intake to meet the animal's requirements, NH3 and N2O emissions are reduced.
- Total emissions savings 2020: 0 MtCO2eq
- Total emissions savings 2045: 0.07 MtCO2eq (0.2%)
- Assumptions: Applied to 100% of monogastrics, 100% of the indoor time of dairy cows and 50% of the indoor time of other ruminants.
- Average emissions reduction: 20% NH3 for pigs and hens, 15% NH3 for dairy and 10% NH3 for poultry fattening. Reductions in N2O are not specified as they are indirectly influenced by reductions in NH_3 emissions. Lower NH_3 emissions generally lead to reduced N_2O emissions, since NH_3 is a precursor to N_2O formation in soil.
- Source: CAPRI, Pérez Domínguez et al. (2020)

Tables A12, A13 and A14 show the adoption rates of the mitigation technologies modelled by CAPRI. The additional mitigation technologies are not included in the tables as they have an assumed 0% adoption rate for 2020. Adoption rates of 25%, 50% and 75% are calculated for 2045.

Adoption rates in cattle husbandry

→ Table A12

Mitigation technology	2020 (%)	2045 scenario (%)
Breeding for ruminant feed efficiency	1	94
Anti-methanogen vaccination	0	33
Low-protein feeding	0	5
Linseed as a feed additive	0	12
Nitrate as a feed additive	0	24
Anaerobic digestion based on size effect on cost	1	15

Adoption rates in pig fattening and breeding → Table A13

Mitigation technology	2020 (%)	2045 scenario (%)
Low-protein feeding	0	14 (fattening) & 3 (breeding)
Anaerobic digestion based on size effect on cost	3 (fattening) & 4 (breeding)	68

Adoption rates in laying hens and poultry fattening → Table A14

Mitigation technology	2020 (%)	2045 scenario (%)
Low-protein feeding	0	5 (poultry fattening) & 25 (laying hens)

5.4 Effect of peatland rewetting on cattle farming (Chapter 4.4.1 Section C)

To assess the impact of peatland rewetting on cattle farming in the EU, a sensitivity analysis is run in CAPRI excluding the rewetting of peatlands, while maintaining all other assumptions of the 2045 scenario. To evaluate the effects, livestock numbers in the respective NUTS-2 regions in 2020 are then compared to the livestock numbers for the 2045 scenario with and without peatland rewetting.

5.5 Arable land use for feed production (Chapter 4.4.2)

This section describes the approach for calculating the area of arable land used for feed production within the EU and for feed imported into the EU. Since CAPRI does not differentiate between feed and food imports, we rely on EU statistics for import data. The total arable land area used for domestic feed production in the EU is estimated at 65.2 million hectares in 2020, about 66% of the total EU arable land. This is calculated using figures from CAPRI and cross-checked with figures from Eurostat (Eurostat 2023d). To calculate the virtual global arable land imported to the EU for feed production, we extract the average feed imports (2011–2022) (European Commission 2022) and divide by the average world yields (given by CAPRI) for the most relevant feed categories (i.e., feed cereals and protein-rich feed). Yield corrections were made for oilseed meals, which are weighed based on their output shares in oilseed processing.

To estimate the area of arable land used for feed production in the 2045 scenario, we start by taking feed consumption data from CAPRI and feed import data from EU statistics. We subtract imports from total consumption to determine domestic production. We then divide this domestic production by the EU average yields for each feed crop category (including forage) to calculate the land area required. We apply an import share of 30% for oilseed meals, as indicated by the CAPRI model, assuming all imports are used as feed. In line with the approach for 2020, we calculate the global arable land used for EU feed production in 2045 using average world yields (given by CAPRI). For feed cereals, we assume an unchanged import share of 13% in 2045.

CAPRI data on total production, weighted average yields for the EU and global yield averages are used for these calculations. Feed-import data is extracted from the EU Feed Protein Balance Sheet European Commission (2022). The results are shown in Tables A15 to A17.

Arable land use in the EU for feed production in 2020

→ Table A15

Feed type	Feed imports 2011–2022 (million tonnes)	Feed consumption 2020 (million tonnes)	Feed production 2020 (million tonnes)	EU arable land for feed 2020 (million ha)
Feed cereals[1]	22.41	149.82	127.40	30.03
Protein-rich feed[2]	22.55	74.79	52.24	16.27
Fodder maize	0	189.27	189.27	4.96
Fodder on arable land[3]	0	162.11	162.11	13.58
Fodder root crops	0	3.54	3.54	0.15
Total EU feed area 2020				64.99

1) Feed cereals include barley, grain maize, oats, rice milled, rye, meslin and other cereals.
2) Protein-rich feed includes rapeseed meal, soybean meal and sunflower seed meal.
3) Fodder on arable land includes annual green fodder including clover and mixtures, lucerne, other perennial green fodder (i.e., legumes) and temporary grassland.

Arable land use in the EU for feed production in the 2045 scenario

→ Table A16

Feed type	Feed consumption 2045 (million tonnes)	Feed production 2045 (million tonnes)	Arable land for feed 2045 (million ha)	Change in EU arable land use in 2045 compared to 2020 (%)
Feed cereals[1]	81.70	71.11[4]	17.33	−42
Protein-rich feed[2]	32.05	22.39[5]	6.18	−62
Fodder maize[3]	85.51	85.51	2.26	−54
Fodder on arable land[3]	62.18	62.18	7.89	−42
Fodder root crops[3]	3.38	3.38	0.13	−9
Total EU feed area 2045			33.8	−42

1) Feed cereals include barley, grain maize, oats, rice milled, rye, meslin and other cereals.
2) Protein-rich feed includes rapeseed meal, soybean meal and sunflower seed meal.
3) The feed categories fodder maize, fodder on arable land and fodder root crops are of 100% EU origin in 2020. We assume them to originate 100% from the EU in 2045 as well.
4) The share of feed cereal imports is assumed at 13%, consistent with the 2020 figures.
5) The share of protein-rich feed from imports are 30%, compared to 46% in 2020.

Virtual global arable land imports for EU feed use in 2020 and the 2045 scenario

→ Table A17

Feed type	Virtual land imports for EU feed 2020 (million ha)	Virtual land imports for EU feed 2045 (million ha)	Relative change in virtual land imports in 2045 compared to 2020 (%)
Feed cereals[1]	5.28[3]	2.58	–51
Protein-rich feed[2]	7.03[3]	2.67	–62
Total global arable land use	12.31	5.25	–57

1) Feed cereals include barley, grain maize, oats, rice milled, rye, meslin and other cereals.
2) Protein-rich feed includes rapeseed meal, soybean meal and sunflower seed meal.
3) Values are calculated using import quantities from the European Commission (2022). Feed imported into the EU includes 22 million tonnes of feed cereals and 23 million tonnes of oilseed meals (soybean, rapeseed and sunflower meal). The virtual arable land import is calculated for cereals and oilseed meals using weighted world average yields.

5.6 Annual costs of improving animal welfare (Chapter 4.4.4 Section B)

We calculate the annual costs of higher animal welfare for beef and dairy cattle, pig fattening, poultry fattening and laying hens to range between 10 and 20 billion euro. Key welfare measures include increased space, better health monitoring, additional organic enrichments and outdoor access. These costs vary by livestock species and are based on the projected EU livestock population in our 2045 scenario.

The average production costs increase by 17.8% due to measures for animal welfare. The costs are listed in descending order per livestock species. Table A18 presents the costs of higher animal welfare for the EU based on 2045 production data and 2020 price data obtained from CAPRI.

Fattening pigs

- Lowest cost increase: 21.7%
- Description (minimum improvement): Providing a minimum of 10% more space than currently required by law, providing stall housing, incorporating organic and crude fibre-rich feeding materials and implementing quality-controlled feed and animal health monitoring.
- Maximum cost increase: 36.1%
- Description (maximum improvement): Offering a minimum of 40% more space than currently required by law, providing stable housing with outdoor climate stimuli, incorporating additional organic bedding material and implementing stringent feed and health-monitoring practices.
- Average cost increase: 28.9%
- Sources: Achilles & Fritzsche (2013), Kirner & Stürmer (2023), Küest (2014), Majewski et al. (2012), Spoolder et al. (2011), WBAE (2015)

Broilers

- Lowest cost increase: 15.8%
- Description (minimum improvement): Allowing a maximum stocking density of 35 kg/m², providing cage-free housing and organic enrichments, using robust breeding lines and ensuring quality-controlled feed and health monitoring.
- Maximum cost increase: 25.7%
- Description (maximum improvement): Allowing a maximum stocking density of 25 kg/m² or 29 kg/m² with access to outdoor climate areas, incorporating additional organic enrichments, using slow-growing breeds and maintaining stringent feed and health monitoring practices.
- Average cost increase: 20.7%
- Sources: Ellen & Leenstra (2012), Gocsik et al. (2016), Spoolder et al. (2011), Vissers et al. (2019, WBAE (2015)

Laying hens

- Lowest cost increase: 7.5%
- Description (minimum improvement): Allowing a maximum stocking density of 28 kg/m², providing cage-free housing and organic enrichments, using robust breeding lines, and ensuring quality-controlled feed and health monitoring.
- Maximum cost increase: 23.7%
- Description (maximum improvement): Allowing a maximum stocking density of 25 kg/m² or 29 kg/m² with access to outdoor climate areas, incorporating additional organic enrichments, employing robust breeding lines and maintaining stringent feed and health monitoring practices.
- Average cost increase: 15.6%
- Sources: Majewski et al. (2012), Van Horne (2019), WBAE (2015)

Dairy cows

- Lowest cost increase: 8.3%
- Description (minimum improvement): Providing adequate playpen space with cubicles or loose housing, utilizing free stall housing or combined rearing with grazing, ensuring pain relief in case of dehorning practices, offering comfort facilities, and maintaining quality-controlled feed and health monitoring.
- Maximum cost increase: 19.3%
- Description (maximum improvement): Providing increased playpen space or pasture area per animal, incorporating all-year-round usable exercise yards, ensuring pain relief in case of dehorning practices, offering comfort facilities, and maintaining stringent feed and health monitoring practices.
- Average cost increase: 13.8%
- Sources: Deblitz et al. (2021), Fuchs et al. (2021), Holzner (2022), Ippenberger & Hofmann (2022), Jürgens & Becker (2021), Ketelsen et al. (2017), Tergast (2023), Thiele & Thiele (2020)

Beef cattle

- Lowest cost increase: 6.0%
- Description (minimum improvement): Providing adequate free stall space based on weight categories, providing loose housing or combined rearing with grazing, ensuring pain relief in case of dehorning practices, and maintaining quality-controlled feed and health monitoring.
- Maximum cost increase: 14.0%
- Description (maximum improvement): Providing increased free stall space or access to pasture, incorporating all-year-round usable exercise yards, ensuring pain relief in case of dehorning practices, and maintaining stringent feed and health monitoring practices.
- Average cost increase: 10.0%
- Sources: Deblitz et al. (2021)

Total animal welfare cost increases for the EU based on the 2045 scenario → Table A18

Livestock product	Annual production in 2045 (1 000 tonnes)	Price in 2020 (euro per tonnes)	Production value 2045 at 2020 prices (billion euro)	Minimum additional costs for animal welfare (billion euro)	Maximum additional costs for animal welfare (billion euro)
Raw milk	100 412.0	334.7	33.6	2.8	6.5
Pig meat	9 006.9	1 801.0	16.2	3.5	5.9
Poultry meat	9 560.4	1 345.7	12.9	2.0	3.3
Beef/veal	6 790.3	3 397.1	23.1	1.4	3.2
Eggs	4 731.2	1 233.2	5.8	0.4	1.4
Total	130 500.8		91.6	10.1	20.3

6 Arable farming (Chapter 4.5)

6.1 Reduction of gross nitrogen balance surpluses (Chapter 4.5.1 Section A)

We aim at halving the gross nitrogen balance (GNB) surplus in EU agriculture by 2045 compared to 2020. In our 2045 scenario, the EU's overall GNB surplus decreases by 54% compared to 2020.

Short method description

In the CAPRI analysis, we reduce GNB surpluses in the EU according to the approach of Barreiro-Hurle et al. (2021), but make some adjustments. Barreiro-Hurle et al. (2021) pursue a two-step approach:
- A 75% nitrogen use efficiency is set as a target for each NUTS-2 region.
- NUTS-2 regional GNB surpluses are reduced by setting progressive reduction targets.

In contrast to Barreiro-Hurle et al. (2021), we:
- Do not specify a fixed target value for nitrogen use efficiency,
- Do not implement reduction factors for regional GNB surpluses below 25 kg nitrogen per hectare per year.

Data

The GNBs documented in CAPRI form the basis for the calculation.

CAPRI sources input data from:
- FAOSTAT data for the use of non-organic nitrogen fertilisers on the level of EU member states,
- Expert questionnaire data from the International Fertilizer Industry Association on average mineral fertiliser application rates per crop and country,
- The cooperative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe (also called EMEP) for nitrogen deposition.

All other aspects of the nitrogen balances are modelled either in CAPRI or associated models like GAINS and MITERRA-EUROPE. For further details see Leip et al. (2011).

The nitrogen balances issued by CAPRI deviate from the officially reported values. Özbek et al. (2015), for example, provide a comparison.

Calculation

Progressive reduction factors are applied to GNB surpluses by NUTS-2 region. For each region, reductions are implemented in tranches based on the GNB in 2020 (Table A19 and Figures A1 and A2).

Progressive reduction factors for regional GNB surpluses in the 2045 scenario

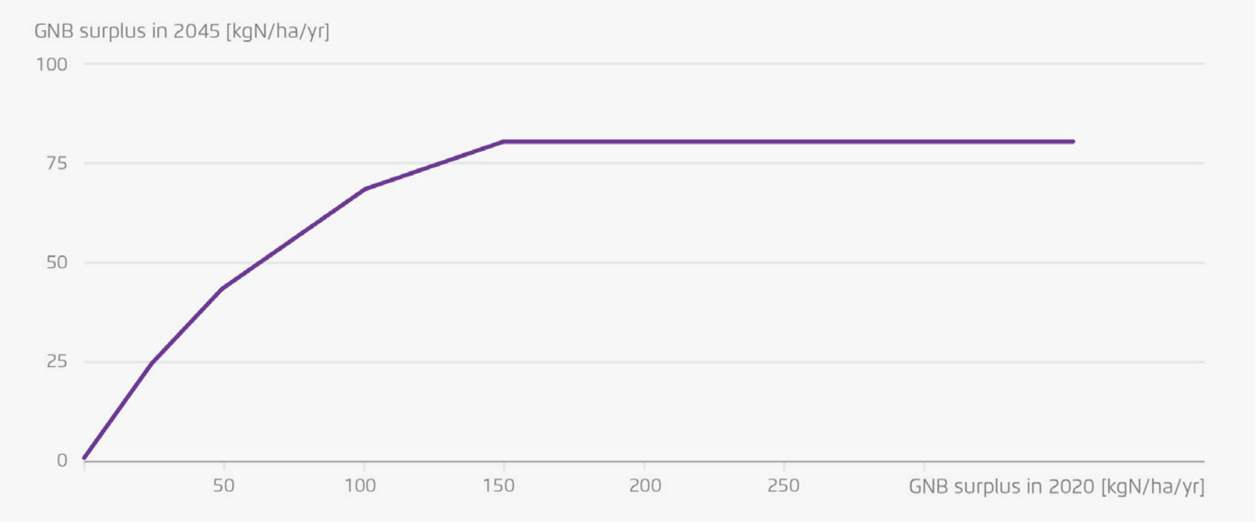
→ Table A19

Tranche (kg N/ha/yr)	Relative reduction in this tranche (%)	Maximum reduction in this tranche (kg N/ha/yr)
<25	0	0
25–50	25	6.25
50–100	50	25
100–150	75	37.5
>150	100	Unlimited

As a result, the maximum GNB surplus at the NUTS-2 level is 81.25 kg nitrogen per hectare per year.

Maximum Gross Nitrogen Balance (GNB) surpluses in 2045 depending on the initial situation in 2020

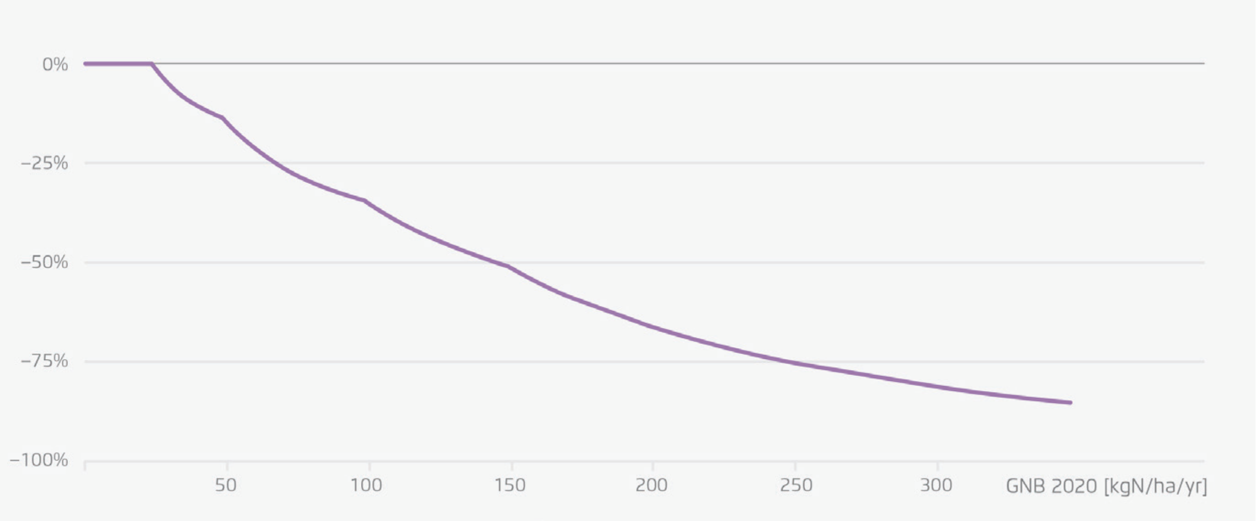
→ Figure A1



Agora Agriculture

Progressive minimum reduction based on the Gross Nitrogen Balance (GNB)surplus per NUTS-2 region in 2020

→ Figure A2



Agora Agriculture

Results

The EU total gross nitrogen balance surplus declines by 54% in the 2045 scenario. The regional maximum reduction is 89% and the lowest reduction is 12% at NUTS-2 level. The reduction in the total application of synthetic mineral nitrogen fertilisers is 43%. The reduction in total nitrogen from manure is 53%. EU average reduction of total nitrogen input is 25% on productive arable land, 10% on vegetables and permanent crops and 29% on grassland.

6.2 Greenhouse gas mitigation technologies (Chapter 4.5.1 Section A)

Mitigation technologies can help to reduce greenhouse gas (GHG) emissions from arable farming. We estimate their mitigation potential to be about 8 million tonnes of carbon dioxide equivalent ($MtCO_2eq$) by 2045.

Short method description

CAPRI provides a catalogue of GHG mitigation technologies that can be activated. For a full overview of these technologies, see Pérez Domínguez et al. (2020). We factor in the uptake of the following mitigation technologies:
- Nitrification inhibitors,
- Better timing of fertilisation,
- Precision farming (composite measure),
- Variable rate technology,
- Combined measures for rice cultivation.

We deactivate the following mitigation options in CAPRI:
- Winter cover crops,
- Increasing legume share on temporary grassland.

We deactivate these options in CAPRI due to concerns about the underlying assumptions regarding their climate impact. Especially in the long-term perspective, we are cautious about the potential of CO_2 sequestration in cultivated arable soils.

In the case of winter cover crops, the assumption in Pérez Domínguez et al. (2020) is that 100% legumes are grown, which we do not consider realistic. In the case of an increased share of legumes on temporary grassland, we consider the assumed sequestration rate of 400 kg carbon per hectare and year by Pérez Domínguez et al. (2020) to be overestimated (Annex Chapter 3). Deactivating these options in CAPRI is based on these considerations and does not reflect a lack of recognition of their relevance for climate protection and adaptation in arable farming.

In addition to GHG mitigation technologies in arable farming, the CAPRI catalogue also includes processes for the low-emission application of manure fertilisers. Their primary function is to avoid ammonia emissions by reducing surface exposure of manure fertilisers. However, they can also have an impact on nitrous oxide (N_2O) emissions, which are also accounted for in CAPRI (Klimont & Brink 2004).

Data

Data is provided by CAPRI.

Calculation

The effect of mitigation technologies on net revenues determines the uptake of these technologies in CAPRI. By setting a carbon price on GHG emissions of 200 euro per tonne CO_2eq we incentivise technology uptake.

For details about the implementation of these mitigation technologies in CAPRI, see Witzke et al (2014).

The following assumptions are key to assessing the climate change mitigation potential of arable farming technologies and measures: 1) The emission factors of the technology alternatives; 2) the agronomic costs and benefits; 3) the current and maximum technology diffusion (Pérez Domínguez et al. 2020). We have left these assumptions in CAPRI unchanged.

Results

Contribution of technological measures to the mitigation of GHG emissions in arable farming in 2020 and 2045

→ Table A20

Mitigation technology	Processes where mitigation takes place	Mitigated emissions in 2020 ($MtCO_2eq$)	Mitigated emissions in 2045 ($MtCO_2eq$)
Nitrification inhibitors	Application of N fertilisers	0.02	5.32
Optimised fertiliser timing		0.02	0.81
Variable rate technology		0	0.06
Precision farming	Farming in general	0	1.51
Combined measures for rice cultivation	Rice production	0	0.55

Diffusion[1] of GHG mitigation technologies in arable farming in 2020 and 2045

→ Table A21

Mitigation technology	Reference area	Uptake in 2020 (%)	Uptake in 2045 (%)
Nitrification inhibitors	UAA	0.1	61.0
Optimised fertiliser timing	UAA	0.1	12.0
Variable Rate technology	UAA	0	0.7
Precision farming	UAA	0	9.0
Combined measures for rice cultivation	Paddy rice	0	100.0

1) The percentages indicate which share of the underlying process is carried out using the respective technology.

6.3 Integration of semi-natural features in agricultural landscapes (Chapter 4.2.1 Section C)

We estimate the arable land needed to provide at least 20% semi-natural landscape features (SLF) in all EU agricultural landscapes in 2045. The existing landscape features are considered in this calculation. The aim is to differentiate the requirements for SLF on arable land on a regional basis.

According to our calculations, 5.3% of productive arable land in the EU must be provided for SLF to achieve 20% semi-natural habitat cover in all agricultural landscapes in the 2045 scenario. At the NUTS-3 level, the share of productive arable land required for a minimum of 20% semi-natural cover ranges between 0% and 17%.

Short method description

We estimate the regional proportion of productive arable land that must be used for semi-natural landscape features so that all agricultural landscapes in the EU have at least 20% SLF.

The reference area for achieving the 20% SLF target comprises land use types categorised as "agricultural land" in the Corine Land Cover 2018 (CLC nomenclature 2XX). From this area, classes with a predefined SLF share exceeding 20% are excluded. In the remaining reference area, woody structures identified by remote sensing are categorised as SLF.

Rewetted arable peatland and permanent grassland are also categorised as SLF in our 2045 scenario.

The percentage of the reference area that must be used for semi-natural landscape elements is calculated. This percentage is multiplied by the productive arable area in CAPRI.

Data

The central data basis is the CLC 2018 with a minimum mapping unit of 25 hectares (EEA 2019). For Germany only, the national dataset LBM-DE 2018 with a minimum mapping unit of 5 hectares is used additionally. [6]

The data set of d'Andrimont et al. (2021) is used to map woody structures on agricultural land.

Administrative boundaries of the NUTS-2 and NUTS-3 regions are taken from the GISCO statistical unit dataset of Eurostat (reference year 2021).[7] As the NUTS-2 regions in CAPRI are not fully congruent with the NUTS-2021 dataset, the NUTS-3 results are aggregated to NUTS-2 level in CAPRI.

Calculation

All calculations are first carried out at NUTS-3 level and then aggregated to NUTS-2 level.

Disclaimer: The following map sections are only intended to explain our approach of how to assess the endowment of agricultural landscapes with semi-natural landscape features. In our analysis, the land requirements for semi-natural landscape features are calculated at NUTS-3 level.

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[6] https://gdz.bkg.bund.de/index.php/default/wms-corine-land-cover-5-ha-stand-2018-wms-clc5-2018.html (accessed 15.03.2024).

[7] https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts (accessed 15.03.2024).

Workflow for the analysis of semi-natural cover in agricultural landscapes → Fig. A3

Agora Agriculture

1. Definition of the reference area on which 20% SLF must be achieved

The basis for determining the reference area is all areas classified as agricultural areas in CLC (CLC nomenclature CLC 2XX "Agricultural Areas"[8]) (Figure A3 Step 1).

Permanent grassland areas (CLC 23X) are deducted from CLC2XX. In our scenario, the intensity of permanent-grassland management is reduced; permanent grassland is therefore categorised as SLF in our analysis. We regard permanent grassland as contiguous landscapes in which the 20% SLF target is met (Figure A3 Step 2).

Vineyards, orchards and olive plantations (CLC classes 22X) are also deducted from CLX 2XX, but they are not categorised as SLF. In our analysis, we do not make any statements about the need for additional SLF in these land use categories (Figure A3 Step 2).

The reference area, on which 20% SLF must be achieved, is made up of CLC classes 21X ("Arable land") and 24X ("Heterogeneous agricultural areas") (Figure A3 Step 3).

Deduction of CLC classes for which the criterion of 20% SLF is met by definition

CLC classes for which the criterion of >20% semi-natural habitat is met by definition are deducted from the reference area:

– CLC 243	Land principally occupied by agriculture, with significant areas of natural vegetation
– CLC 244	Agroforestry areas[9]
– CLC 242	Complex cultivation patterns[10]

The remaining area, on which 20% SLF need to be established is shown in Figure A3 Step 4.

2. Deduction of woody landscape features in arable-dominated landscapes

Due to the minimum mapping unit of 25 hectares, small woody features in agriculturally dominated landscapes are counted as agricultural land in the CLC 2018. However, these woody features are valuable habitats and are therefore taken into account when calculating the area required for SLF.

We use raster data from d'Andrimont et al. (2021) with a grid width of 10 metres. Raster cells with the value 300 (woodland and shrubland type of vegetation) that lie within the CLC vectors 21X and 241 are counted. Each cell (100 square metres) fulfils the 20% SLF criterion for 500 square metres of surrounding agricultural land. Accordingly, the area of the counted grid cells is multiplied by a factor of 4 (Figure A3 step 5) and subtracted from the reference area (Figure A3 step 6).

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[8] For detailed information on the definition of CLC classes see: https://land.copernicus.eu/content/corine-land-cover-nomenclature-guidelines/html/index.html (accessed 26.03.2024).

[9] CLC 244 includes both agroforestry on arable land and on permanent grassland without the respective area shares being known, only half of the area is subtracted from the reference area as an approximation. This land use category is relevant only in a few regions in the Mediterranean (i.e., dehesas in Spain and montados in Portugal and Sardinia).

[10] CLC 242 subsumes mosaics of small, cultivated land parcels with different cultivation types, none of them occupying > 75% of the area. We subtract 75% of the area of CLC 242 from the reference area as an approximation.

3. Special case Germany

Germany does not report land use classes 24X to pan-European CLC (BKG 2022). Germany reports on the basis of a land cover model (Basis-DLM) with a minimum mapping unit of 1 hectare.[11]

Against this background, we mimic CLC 242 for Germany by intersecting the CLC maps with a minimum mapping unit of 25 hectares and 5 hectares:

- The German CLC (CLC5 2018) vector data is rasterised to a 10-metre grid.
- Raster cells with the CLC code 231 and 321 (Natural grasslands) that lie within CLC classes 21X (25 hectares minimum mapping unit) are counted. These represent permanent grassland < 25 hectares within arable-dominated agricultural landscapes. Assuming that this residual grassland is preserved and farmed less intensively in 2045, it is categorised as SLF.
- Each cell (100 square metres) fulfils the 20% SLF criterion for 500 square metres of surrounding arable land. Accordingly, the area of the counted grid cells is multiplied by a factor of 4 and subtracted from the reference area.

4. Calculation of the share of productive arable land to be used for SLF

After deducting woody features in arable-dominated landscapes in the EU (and after deducting residual grassland in arable-dominated landscapes in Germany) the result is the arable land on which the 20% SLF criterion is not yet met.

This area is multiplied by a factor of 0.2 to calculate the arable land to be used as semi-natural landscape features in 2045.

The result is set in relation to the reference area (CLC 21X + CLC242).

5. Aggregation at NUTS-2 level

The results calculated at the NUTS-3 level are aggregated at the NUTS-2 level.

As the NUTS-2 vectors in CAPRI do not correspond to the current (2021) NUTS-2 levels in all EU member states, manual recalculations are carried out for the corresponding regions.

6. Differentiation between productive and non-productive SLF

In our scenario, we set the target of 20% of the area in agricultural landscapes being covered with semi-natural landscape elements. Half of this (i.e., 10% of the area) should be used unproductively.

To quantify what proportion of the arable land required to achieve the 20% SLF target must be used for productive and non-productive SLF, we calculate how many unproductive SLF are already available.

We categorise all existing SLF as unproductive, except for residual grassland in arable-dominated landscapes (i.e., 25% of 242, respectively residual grassland in arable-dominated landscapes in Germany
(see Point 4).

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[11] The base layer with a minimum mapping unit of 1 hectare is not licence-free, so the freely available German CLC dataset with a minimum mapping unit of 5 hectares (CLC5 2018) is used for our analysis.

The shortfall of 10% of unproductive SLF must be covered with additional unproductive SLF on arable land; the remainder of the area required for SLF can be used productively.
Part of the productive SLF is used for qualified photovoltaic systems and for linear-shaped fast-growing trees for biomass production. Details can be found in Annex Chapter 3.

We classify the remaining productive SLF area as extensive grassland.

7. Offsetting of rewetted agricultural land and CAPRI land category "FALLOW"

In the 2045 scenario, we assume that 80% of thcae peatlands used for agriculture are rewetted. Of this rewetted area, 80% is used for biomass production. The remaining 20% of the rewetted land is wilderness and photovoltaics. Against this background, we consider rewetted peatlands to be contiguous landscapes in which the 20% SLF criterion is met.

Rewetted arable peatland is deducted from the land requirement for SLF.

In addition to crops, CAPRI also issues land for fallow land (CAPRI land category "FALLOW"). These areas are also deducted from the arable land to be used as SLF in 2045 at NUTS-2 level.

Results

In total, 5.3% of the productive arable land in the EU is used for SLF by 2045, varying between 0% and 17.0% across NUTS-3 regions. On average across the NUTS-3 regions, only just under 1% of productive arable land is required for unproductive SLF (max. 7.7%), which means that more than 80% of additional SLF on arable land can also be used for production-integrated measures.

6.4 Management of small cropping units and crop diversification (Chapter 4.5.1 Section C)

Short method description

Changes in the size of cropping units/plots are not modelled in CAPRI.

Crop diversification is addressed by defining maximum shares of crop types on NUTS-2 level. Table A22 shows the maximum crop shares used as input restrictions in CAPRI.

Data

Data is provided by CAPRI.

Calculation

Values for maximum crop shares are taken from Jeangros & Courvoisier (2019), Kolbe (2008), Diepenbrock et al. (2016) and Land24 GmbH (2024).

Maximum shares of crop types per NUTS-2 region in the 2045 scenario → Table A22

Crop group	Crop type / subgroup	Maximum share (%)
Cereals	Soft wheat	33
	Durum wheat	50
	Rye and meslin	50
	Barley	40
	Oats	25
	Paddy rice	33
	Maize	50
	Other cereals	50
Oilseeds	Rapeseed	25
	Sunflower	25
	Soya	25
Other annual crops	Pulses	25
	Potatoes	25
	Sugar beet	25
	Flax and hemp	25
	Other industrial crops	50
Vegetables	Tomatoes	25
	Other vegetables	50
Others	Other marketable crops	50
Fodder production	Fodder maize	40
	Fodder root crops	25
	Other fodder on arable land	50

6.5 Reduction in the use of plant protection products (Chapter 4.5.1 Section C)

We aim for a 50% reduction in the application of Plant Protection Products (PPP) in 2045 compared to the year 2020. We assume that a 15% reduction can be achieved without any effect on yields. Therefore, the restriction in CAPRI is set to 35% for each NUTS-2 region.

The total reduction in PPP use achieved in our 2045 scenario is 52% compared to 2020 levels.

We do not apply a risk weighting based on the toxicological profile of PPPs.

Short method description

CAPRI distinguishes between five aggregated PPP categories:
- Fungicides and bactericides,
- Herbicides,
- Insecticides and acaricides,
- Growth regulators,
- Other pesticides.

The application rates of these PPPs have direct effects on yields. The overall reduction target is binding in each NUTS-2 region. It applies to the total quantity of PPP used. The model allows for efficient allocation of this reduction across crop types and PPP categories.

Data

Data is taken from CAPRI. The model aggregates PPP data from Eurostat.

Calculation

CAPRI calculates damage-avoidance functions of PPP application on yields for all combinations of crop types, PPP categories and NUTS-2 regions. For a detailed description see Witzke et al. (2021).

Results

The overall reduction of PPP use in our 2045 scenario is 52%. PPP reduction per hectare is 49% on arable land and 39% on vegetables and permanent crops. The increase in SLF reduces the amount of land on which PPP are applied. As a result, the 49% reduction per hectare is smaller compared to the overall reductions in PPP use.

Relative reduction[1] of per-hectare application rates of different functional groups of plant protection products as modelled in CAPRI. → Table A23

CAPRI crop category	Fungicides and bactericides (%)	Herbicides (%)	Insecticides and acaricides (%)	Growth regulators (%)	Other PPP (%)	Total PPP (%)
Total agricultural area	−30	−46	−20	−42	−27	−34
Cereals	−28	−40	−25	−28	−33	−33
Soft wheat	−20	−29	−6	−29	−22	−23
Durum wheat	−29	−37	−6	−23	−33	−30
Rye and meslin	−22	−41	−31	−45	−41	−35
Barley	−13	−40	−28	−25	−38	−27
Oats	−26	−37	−30	−38	−19	−35
Grain maize	−20	−30	−2		−30	−26

Other cereals	–12	–36	16	–31	–13	–26
Paddy rice	–8	–15	–19	–19	–3	–13
Oilseeds	–19	–32	–21	–30	–35	–28
Rapeseed	–21	–32	–18	–29	–32	–28
Sunflower	–22	–35	–11	–25	–44	–31
Soya	4	–8	0	–4	–2	–5
Other oils	–5	–17	–4	4	–5	–13
Other arable crops	–63	–54	–50	–60	–42	–56
Pulses	–19	–28	–34		–31	–30
Potatoes	–8	–19	9	–9	0	–7
Sugar beet	–24	–28	–7		–22	–23
Flax and hemp	33	–24	38	7	39	–8
Tobacco	–22	–16	–23	7	–40	–18
Other industrial crops	–23	–29	–34	–26	–28	–29
Other crops	-31	–33	–27	–30	–30	–32
Vegetables and permanent crops	–25	–27	–7	–4	–28	–24
Tomatoes	–1	–1	–2		–1	–1
Other vegetables	–8	–8	–1	–17	–8	–8
Apples, pears and peaches	–20	–23	0	–24	–22	–16
Other fruits	–12	–33	–9	–24	–10	–12
Citrus fruits	–13	–31	–9	–36	–18	–14
Table grapes	–10	–9	–6	–5	–9	–10
Olives for oil	–39	–39	–22	–38	–37	–37
Table olives	–15	–26	–1	–32	–17	–14
Wine	–16	–30	–3	–22	–15	–15
Nurseries	–42	–41	–44	–45	–42	–43
Flowers	–31	–30	–30	–29	–30	–31
New energy crops (ligneous)						
Fodder activities	–39	–44	–67	–36	–42	–45
Fodder maize	–28	–33	–38		–46	–35
Fodder root crops	–34	–43	–28		–36	–39
Fodder other on arable land	–41	–41	23	–41	–25	–39
Grass and grazings extensive	–25	–24	–12	–25	–24	–24
Grass and grazings intensive	–42	–43	–45	–49	–56	–44

1) The presumed 15% reduction without effect on yields is not included in this table.

PPP average application rates on arable land without vegetables in kg per hectare → Table A24

Year	Fungicides (kg/ha)	Herbicides (kg/ha)	Insecticides (kg/ha)	Other PPP (kg/ha)	Other PPP (kg/ha)	Total PPP (kg/ha)
2020	0.68	0.96	0.21	0.13	0.09	2.08
2045	0.48	0.59	0.16	0.09	0.06	1.37
Relative change (%)	–30	–39	–26	–30	–28	–34

PPP average application rates on fruits, vegetables and other permanent crops in kg per hectare → Table A25

Year	Fungicides (kg/ha)	Herbicides (kg/ha)	Insecticides (kg/ha)	Growth regulators (kg/ha)	Other PPP (kg/ha)	Total PPP (kg/ha)
2020	7.40	0.62	1.51	0.03	3.01	12.57
2045	5.52	0.45	1.40	0.03	2.17	9.57
Relative change (%)	–25	–27	–7	–4	–28	–24

6.6 Biomass and bioenergy potentials from agricultural residues, organic municipal waste and biomass from landscape conservation (Chapter 4.5.1 Section D)

We quantify both the theoretical and technical biomass and bioenergy potentials for biomass and bioenergy from agricultural residues, organic municipal waste and biomass from landscape conservation for anaerobic digestion.For the production pattern of arable farming in our 2045 scenario, we estimate the technical potential at 625 TWh.

We do not quantify the economic potential for the anaerobic digestion from agricultural residues, organic municipal waste and biomass from landscape conservation substrates. Only a portion of the technical potential would be economically feasible to implement. For a definition of biomass potentials see Offermann et al. (2011).

Short method description

We quantify the theoretical and technical biomass and bioenergy potentials of the following groups of feedstocks:
- Catch and cover crops,
- Crop residues (straw and haulm, etc.) from arable land,
- Manure from animal husbandry,
- Biomass from the maintenance of semi-natural landscape features (e.g., rotational fallow, field margins, riparian and buffer strips, extensive grasslands, etc.),
- Organic municipal waste (biowaste and green waste, sewage sludge, industrial wastewater, etc.).

Energy crops are excluded from this calculation.

Data

Biomass and bioenergy potentials are estimated using a calculation tool developed by the German Institute for Biomass Research (DBFZ) for Agora Agriculture.

Production patterns, main crop yields and animal numbers are taken from the CAPRI output of the 2045 scenario.

Sources of other input data in the DBFZ tool:
- Data on barn types and management practices affecting manure capture: Vos et al. (2022),
- Biowaste for the year 2020: Günther et al. (2023),
- Sewage sludge for the year 2016: Bellot et al. (2021).

Sources for the factors used for the calculation of biogas yields in the DBFZ tool:
- Biogas yields of different types of manure: German "Düngeverordnung" (DüV)[12],
- Dry matter contents of different types of manure: KTBL (2024c),
- Biogas yields during anaerobic digestion: LfL Bayern (2024), KTBL (2024c), expert estimates from DBFZ,
- Other: Other literature and expert estimates.

Yields per hectare of SLF are sourced from three different German institutions (DBFZ, KTBL and FNR) and expert estimates.

Calculation

We calculate both the theoretical and the technical biomass potential as well as corresponding biogas potentials. The theoretical potentials include all the biomass growing on the input areas, plus municipal waste. The technical potential is limited by technical restrictions (e.g., losses during harvesting, transport and storage). It does not include legal or logistical constraints.

We use the lower bound of yields per hectare to obtain a conservative estimate.

Catch and cover crop area are deduced from main crop production patterns in the 2045 scenario (Table A26). The following crops are assumed to be fully compatible with catch and cover crop production for anaerobic digestion: maize, sunflower, soya, potatoes, sugar beet, flax and hemp. Summer varieties of cereals are typically sown very early, which generally prevents high-yield catch crop production. Consequently, we consider areas cultivated with cereals to be unsuitable for catch and cover crops in this estimate.

Additionally, we do not make assumptions about changes in the volume of biowaste, sewage sludge and other municipal waste between 2020 and 2045.

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[12] https://www.gesetze-im-internet.de/d_v_2017/BJNR130510017.html (accessed 07.08.2024).

Suitable catch crop areas per main crop

→ Table A26

Crop	2045 area suitable for catch crops for anaerobic digestion (1 000 ha)
Grain maize	4 084
Sunflower	4 447
Soya	1 329
Potatoes	795
Sugar beet	489
Flax and hemp	222
Fodder maize	2 260
Total	13 626

We assume that permanent grassland already used extensively in 2020 is unsuitable for biogas feedstock production due to natural or infrastructural reasons (e.g., it is too steep or remote). Therefore, this area is excluded from our potential estimates. In CAPRI, grassland farming intensity is represented by the proportion of intensive and extensive grassland. We use these areas as proxies for grassland that is intensively farmed versus semi-intensively or extensively farmed (Table A27).

Consequently, the roughage demand for the ruminant herd in 2045 will be fully met by the remaining intensive grassland and arable leys. Therefore, the yield from permanent grassland that is intensively used in 2020 but is projected to be semi-intensively or extensively farmed in 2045 is included in the calculation of the theoretical and technical biomass potential for anaerobic digestion.

Grassland area harvestable for anaerobic digestion in 2045

→ Table A27

Headline	Area (1 000 ha)
Semi-intensive or extensive grassland in 2020	24 082
Semi-intensive or extensive grassland in 2045	40 869
Grassland area harvestable for anaerobic digestion	16 787

Animal numbers in CAPRI represent heads slaughtered per year. This number is translated to barn capacity to properly assess manure quantities. For pigs, the number of production cycles year is 2.90 in our scenario; for poultry fattening it is 6.26.

The proportion of manure that can be collected in barns depends on the share of grazing time throughout the year. The manure may be solid or liquid. The proportions of solid and liquid manure add up to 1. For this calculation we make no assumptions on the evolution of stable types and the share of grazing time (Table A28). Values reflect the situation in Germany around 2020. Due to a lack of data at the EU-level, the German shares are assumed for the whole EU. The same shares are used for 2045.

Shares[1] of stables with liquid manure and shares of grazing time for CAPRI animal categories. → Table A28

CAPRI animal category	Share of stables with liquid manure (%)	Share of grazing time (%)
Dairy cows	87	7
Other cows	19	56
Heifers	58	16
Male adult cattle	48	28
Male calves	26	4
Female calves	24	7
Sheep	0	55
Pig fattening	96	0
Pig breeding	93	0

1) Values reflect the situation in Germany around 2020

Results

The theoretical biogas potential for the 2045 scenario is 742 TWh. The technical biogas potential for the 2045 scenario is 625 TWh.

6.7 Production and markets (Chapter 4.5.2)

Short method description

Market balances illustrate different production and use categories in a given year along with external trade.

For soya, other pulses and several fruits and vegetables, the impact of investment into the development of value chains is modelled as a shift in supply functions.

In addition to the shift in the supply functions, we assume an increase in yield for soya and other pulses by 10% at constant input due to advances in breeding and cultivation. This is additional to the projection of yield trends into the future which is already included in the CAPRI model.

Data

CAPRI provides detailed data at the NUTS-2 level, member state level and EU level.

For EU-27 market balances, we use total EU trade without intra trade. Market balances contain the following elements:

- "Net production"
  This refers to the total output minus the quantity of seeds set aside for the next year's sowing.
- "Human consumption plus losses"
  This is the sum of "intake", "losses at consumption stage" and "losses at market stage".
- "Processing" and "Biofuels processing"
  The processing categories indicate that the respective quantities are converted into another product. These quantities are also listed in the "net production" category of the respective processing products.
  For example:
  - Oilseeds are converted into oil and cake.
  - Cereals and most other grains are converted partly into by products used for feed concentrate and into biofuels.
- "Feed use"
  The quantity of the respective product directly fed to animals without processing.
- "Imports without intra trade"
- "Exports without intra trade"
- "Net trade"
  Net trade = exports without intra trade – imports without intra trade.

The balances of all products and product categories follow the equation:

Net production + imports = human consumption including losses + feed use + exports + processing + biofuel processing.

For graphic representation, we define the following categories:
- Production = Net production,
- Human consumption = Overall food intake without losses,
- Feed use = Feed use,
- Other = Processing, Biofuel processing, Losses at consumption and market stage,
- Net trade = Net trade.

We aggregate some of the CAPRI products into product groups:
- Cereals: Wheat, rye and meslin, barley, oats, grain maize, other cereals,
- Fruits: Apples, pears and peaches, table grapes, citrus fruits, other fruits, table olives,
- Vegetables: Tomatoes, other vegetables.

Calculation

Shift in supply functions for soya, pulses, fruit and vegetables

For several agricultural production activities, we shift their supply functions to the right along the quantity axis. This reflects an increased supply quantity at a given price.
- Pulses: 100% to the right,
- Soya: 100% to the right,
- Apples, pears, peaches: 150% to the right,
- Other fruits (OFRU in CAPRI): 40% to the right,
- Vegetables other than tomatoes (OVEG in CAPRI): 20% to the right.

Market balances

In the case of rapeseed, sunflower and soya balances, the calculation of first-stage production and processing products is as follows:
- "Net production" is the sum of the net production of the seeds,
- "Processing" is the sum of the processed quantities of oils and oil cakes.

In the market balances, we differentiate between human consumption and losses by applying loss shares from CAPRI at both the consumption stage and markets level.

6.8 Estimation of the costs for establishing and managing multifunctional agricultural landscapes (Chapter 4.5.1)

We estimate the magnitude of costs for the establishment and management of multifunctional agricultural landscapes. Measures included are the integration of semi-natural landscape features (SLF), the management of small cropping units, diversified crop rotations and extensive grassland management.

We estimate cost ranges between a minimum bound and an upper bound. The cost of implementing agri-environmental measures can vary depending on the location, farm type, production system and market conditions. To approximate these differences, we use regional land rents as a proxy.[13]

We estimate that the annual opportunity cost (costs incurred and income foregone) for managing multifunctional agricultural landscapes range from 9 to 20 billion euro. Additionally, we estimate investment costs could amount to up to 87 billion euro in the period up to 2045.

Short method description

We estimate costs for the following building blocks of multifunctional agricultural landscapes:

1. 20% semi-natural landscape features at landscape level
   We calculate annual opportunity costs (costs incurred and income foregone) and investment costs separately for productive and nonproductive SLF.
   The lower bound assumes mulching fallow land once per year. The costs linked to mulching are derived from a KTBL web-application (KTBL 2024a). The lower bound comes without investment costs.
   The upper bound assumes the planting and maintenance of hedgerows. We used German agri-environmental programmes to estimate costs incurred and foregone income. For investment costs, we also use a German agri-environmental programme. These costs are then weighed per NUTS-2 region using regional land rents.

2. Diversification of crop rotations, reduced plot sizes and grassland extensification
   Upper and lower bounds for opportunity costs are estimated based on German agri-environmental programmes. These costs are then weighed per NUTS-2 region using regional land rents.

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[13] We are aware that the statistically recorded rental prices do not always accurately reflect the opportunity costs of arable farming. For example, the rental market in France is strictly regulated. Every year, a minimum and maximum price is defined per type of land per département. Shadow rental prices therefore have been estimated using econometric models (Chakir & Lungarska 2017, Lungarska & Jayet 2014).

Data

All cost rates are based on sources not older than five years. We have not adjusted for inflation.

20% semi-natural landscape features at landscape level

The area required for semi-natural landscape features (SLF) on arable land in 2045 is calculated as explained in Annex Chapter 3.3. For land rents we use a five-year average (2018–2022) of land rental prices taken from Eurostat per NUTS-2 region where available for arable land (Eurostat 2024a). If data for arable land is not available, we use (in hierarchical order and at NUTS-2 level):

1. Land rents for arable + permanent grassland from Eurostat. We adjust those values using the ratio of arable land rents to arable + grassland rents in the EU from Eurostat.
   EU ratio = five-year average of arable land rents/(five-year average of arable land rents + grassland rents) = 1.11.
2. Data on land rents from the Farm Accountancy Data Network (FADN) (European Commission 2024): We use data from 2020 for the farm type (1) Fieldcrops. We divide the total value of "rent paid" (SE375) by the area of "rented UAA" (SE030).
3. Arable + permanent grassland land rents from the German "Regionaldatenbank Deutschland" (Statistische Ämter des Bundes und der Länder 2024), corrected with the EU ratio, see 1.

The lower bound for SLF maintenance costs is derived from KTBL "Verfahrensrechner Pflanze" (KTBL 2024b), which quantifies the cost of mulching fallow land once per year at 96 euro per hectare per year. Opportunity costs are assessed using land rents specific to the respective NUTS-2 regions.

The upper bound for maintenance costs of production-integrated SLF is derived from a support scheme for wildflower strips in Lower Saxony (Germany) worth 910 euro per hectare per year (Niedersächsisches Ministerium für Ernährung, Landwirtschaft und Verbraucherschutz 2024).

The upper bound for maintenance costs of unproductive SLF is a mixture of two support schemes in Saxony (Germany) for thinning out or cutting of hedges every five years, which is worth an annual 4 895 euro per hectare (SMEKUL 2022b). We assume that hedges are thinned every five years and aboveground biomass is cut every 20 years instead of being thinned. The upper bounds for SLF maintenance costs also cover the opportunity costs associated with arable farming.

The lower bound for investment costs is 0 euro per hectare for fallow land, while the upper bound is based on a support scheme in Saxony (Germany), which provides 75 400 euro per hectare for planting hedgerows (SMEKUL 2022a).

Diversification of crop rotations

The lower bound is derived from the German eco-scheme ES2 "Anbau vielfältiger Kulturen" worth 60 euro per hectare annually (BMEL 2024). The upper bound is derived from the Bavarian (Germany) second pillar CAP programme KULAP K32 "Vielfältige Fruchtfolge mit blühenden Kulturen", worth 100 euro per hectare per year (StMELF 2024). The area of arable land is derived from our 2045 scenario.

Reduced plot sizes

The lower bound is derived from a North Rhine-Westphalian (Germany) second pillar CAP programme for plots of 5 hectares or smaller, worth 35 euro per hectare per year (Landwirtschaftskammer Nordrhein-Westfalen 2024a). The upper bound worth 60 euro per hectare per year is derived from Noack et al. (2023) and refers to plots smaller than 5 hectares. The area of arable land is derived from our 2045 scenario.

Grassland extensification

The lower bound is derived from the German eco-scheme 4 "Dauergrünland Extensivierung Betrieb", worth 100 euro per hectare per year (BMEL 2024). The upper bound is derived from the North Rhine-Westphalian (Germany) second-pillar CAP programme "Extensive Grünlandnutzung" worth 150 euro per hectare per year (Landwirtschaftskammer Nordrhein-Westfalen 2024b). The area of extensively used grassland is derived from our 2045 scenario.

Calculation

20% semi-natural landscape features at the landscape level

The base area is defined at the amount of land required to achieve 20% semi-natural landscape features (SLF) in each agricultural landscape by 2045. This area is further categorized into unproductive SLF and production-integrated SLF (Annex Chapter 6.3). From the area needed for production-integrated SLF, we subtract the area covered by qualified short rotation coppices (i.e., short rotation coppices arranged in linear configurations) and biodiversity photovoltaics on arable land, as these systems are considered economically profitable on their own. It is assumed that photovoltaics are evenly distributed across the SLF area.

We calculate the costs for SLF areas by multiplying the resulting areas with the following:
- The average land rental prices of the respective NUTS-2 regions to calculate the opportunity cost for the lower bound.
- The lower bounds for maintenance costs.
- The upper, combined bounds for maintenance and opportunity costs.
- The upper bound for investment costs (applicable only to unproductive SLF).

Diversification of crop rotations and reduced plot sizes

We multiply the area of arable land per NUTS-2 region with the lower and the upper bounds of costs per hectare. The result is multiplied with the relative level of land rents on arable land in the respective NUTS-2 region compared to the German average. This adjustment is necessary because the cost estimates for the lower and upper bounds are based on German programmes.

Grassland extensification

We multiply the area of extensively managed grassland in each NUTS-2 region by both the lower and the upper bounds of costs per hectare. To estimate regional grassland rents, we first multiply the regional arable land rents with the EU average ratio of grassland rents to arable rents. We then multiply this value with the opportunity cost for extensification. The values for the lower and upper bounds are taken from German CAP programmes. To account for variations in opportunity costs between member states, we use a correction factor that represents the ratio of regional grassland rents to the German average grassland rent.

Results

Total costs incurred and income foregone: 9.1 – 20.4 billion euro per year

- 20% semi-natural landscape features at landscape level
  - Costs incurred and income foregone of production-integrated SLF: 0.4–1.3 billion euro per year,
  - Costs incurred and income foregone of unproductive SLF: 0.4–5.6 billion euro per year.
- Diversification of crop rotations
  - Costs incurred and income foregone: 4.0–6.7 billion euro per year.
- Reduced plot sizes
  - Costs incurred and income foregone: 2.4–4.0 billion euro per year.
- Grassland extensification
  - Costs incurred and income foregone: 1.9–2.8 billion euro per year.

Investment costs for the establishment of semi-natural landscape features: 0.0–86.9 billion euro for the total period up to 2045.

6.9 CO_2 removal potential of planting hedgerows on arable land (Chapter 4.1)

We quantify CO_2 removals from planting hedgerows on arable land.

In our 2045 scenario, we aim for a 10% share of unproductive semi-natural landscape features in agricultural landscapes (Annex Chapter 3.3). We assume that 50% of the arable land used for unproductive semi-natural landscape features in 2045 will be planted with hedgerows.[14] This translates into an area of 576 000 hectares of hedgerows in the EU in 2045.

In a meta-analysis, Drexler et al. (2021) compare carbon stocks of hedgerows with carbon stocks of cropland in the temperate climate zone. They find an average carbon stock of 108.7 tonnes carbon per hectare in hedgerows (including above- and belowground biomass as well as soil organic carbon) compared to cropland with 4.7 tonnes carbon per hectare. Drexler et al. assume CO_2 sequestration in hedgerows to be completed within 20 years after planting. After this period, the carbon stock in hedgerows remains stable, if there is no harvest.

We follow the German national inventory report (Umweltbundesamt 2023) assuming land-use change emissions of 6.58 tonnes carbon per hectare for to the clearing of cropland in the year of hedgerow planting.

We assume a linear pathway for the planting of hedgerows in the EU, resulting in annual planting of 27 000 hectares. The first year of planting is 2025, the last year is 2045.

In our pathway, CO_2 sequestration peaks in 2044 and 2045 with an annual removal of 10.9 $MtCO_2eq$. Between 2025 and 2045, an average of around 5.33 $MtCO_2eq$ will be removed annually.

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[14] This is in line, e.g., with Staley et al. (2023), who recommend a 5% area share of hedgerows in UK landscapes.

7 Agricultural peatlands (Chapter 4.6)

7.1 Peatland emissions reduction (Chapter 4.6.2)

The aim is to assess the reduction of greenhouse gas (GHG) emissions from peatlands in the EU by 2045 compared to 2020. This assessment considers a rewetting scenario in which 80% of the peatlands are fully rewetted, while the remaining 20% are used as shallow drained grasslands by 2045.

In 2020, we estimate GHG emissions of 108 million tonnes of carbon dioxide equivalent ($MtCO_2eq$) from 3.5 million hectares of drained peatlands. By 2045, these emissions are projected to decrease to 36 $MtCO_2eq$. The total reduction in emissions is estimated to reach 72 $MtCO_2eq$, representing a 67% decrease compared to 2020. This reduction includes approximately 35 $MtCO_2eq$ from former arable land on peatlands and about 37 $MtCO_2eq$ from former grassland on peatlands.

These calculations are also used to assess the share of GHG emissions from drained agricultural peatland within the total GHG emissions from agriculture and agricultural peatlands. Additionally, we quantify the share of GHG emissions from agricultural peatlands contributed by the three largest emitting countries (Chapter 4.6).

Short method description

To quantify the GHG mitigation potential of peatland rewetting, we first calculate the total GHG emissions from agricultural peatlands in the EU for 2020. This is done by using the estimated area of peatlands under agricultural use in each EU member state, along with the corresponding GHG emissions per hectare and per year (emission factor, EF) for carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and in CO_2eq.

For 2045, we apply the same method to estimate the residual GHG emissions from:
- the 80% rewetted agricultural peatlands,
- the 20% remaining drained areas assuming that they are used as shallow-drained grasslands.

In our scenario, we assume the rewetting of all arable land on peatland in 2045. In NUTS-2 regions where more than 80% of the agricultural peatland area is arable land, not all arable land on peatland is rewetted in 2045 and the remaining arable land that isn't rewetted is converted to shallow-drained grassland.

Data and calculation

CAPRI estimates of agricultural peatlands in the EU

The area estimates of peatlands under agricultural use in each EU member state are derived from the CAPRI model. In CAPRI, the approach for estimating cropland and grassland on peatlands[15] in NUTS-2 regions integrates multiple data sources and spatial analysis techniques.

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[15] In CAPRI and some of the literature, those areas are referred to as "peatlands" and "organic soils". We use the term "peatlands" because it is more commonly known.

Initial data sources include:
- Country submissions on land use on peatlands from the United Nations Framework Convention on Climate Change (UNFCCC) GHG reporting,
- Cropland and grassland data from the FAO.

GHG emissions from drained and rewetted peatlands

For the calculation of GHG emissions from drained peatlands, we take the Emission Factors (EFs) from the member states national GHG inventory reports (NIRs) provided that they exist and that they are consistent with the 2013 Wetlands Supplement to the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National GHG Inventories (IPCC 2014). When this is not the case, we use default EFs from IPCC (2014).

IPCC (2014) distinguishes grassland categories with respect to nutrient status and water table. As the majority of countries do not make this distinction, we weigh the default EFs for grassland in the temperate climate zone with the following ratio proposed by Martin & Couwenberg (2021):
- 75% of the grassland on peatlands is located on deep-drained, nutrient-rich soils,
- 12.5% is located on shallow-drained, nutrient-rich soils,
- and the remaining share of 12.5% is located on nutrient-poor soils.

Finland and Sweden are the only analysed countries which are not completely in the temperate climate zone. As the EFs differ between the boreal and the temperate climate zone, we weigh them according to the area share located in each climate zone given by Martin & Couwenberg (2021).

We calculate GHG emissions from rewetted peatlands based on the default EF for rewetted peatlands in temperate and boreal climate zones listed in IPCC (2014). As there is no sufficient information about the share of nutrient-rich and nutrient-poor peatlands in each country, we use the EF for nutrient-poor rewetted peatlands in boreal climate zones and the EF for nutrient-rich rewetted peatlands in temperate climate zones. This is consistent with the IPCC (2014) recommendations.

7.2 Budget for rewetting payments for peatlands (Chapter 4.6.4)

The aim is to estimate an annual budget for payments to compensate for the costs of peatland rewetting in the EU, as well as the total budgetary costs between 2025 and 2045. Those calculations are used to show an exemplary path for the budgetary costs of rewetting until 2045 (Chapter 4.6.2, Figure 39).

For the 2.8 million hectares of rewetted peatland in our scenario, the total cost for rewetting payments for the period 2025 to 2045 is estimated at about 12 billion euro. The maximum annual budget is about 1 billion euro around the year 2036.

Short method description

To calculate the annual budget to compensate for peatland rewetting, we estimate the number of hectares rewetted each year from 2025 to 2045 and multiply this by an annual payment per hectare.

Data and calculation

For the calculation of the total rewetted area, see Annex Chapter 7.1. We set an exemplary path for peatland rewetting, assuming a linear increase each year. The annual newly rewetted peatland area increases from about 70 000 hectares in 2025 to about 222 000 hectares in 2044 (Table A29).

Newly and cumulative rewetted peatland area between 2025 and 2045 → Table A29

Year	2025	2026	2027	2028	2029	2030	3031
Newly rewetted area (ha)	70 000	77 330	84 660	91 990	99 319	106 649	113 979
Cumulative rewetted area (ha)	70 000	147 330	231 990	323 979	423 298	529 948	643 927

Year	2032	2033	2034	2035	2036	2037	2038
Newly rewetted area (ha)	121 309	128 639	135 969	143 298	150 628	157 958	165 288
Cumulative rewetted area (ha)	765 236	893 874	1 029 843	1 173 141	1 323 770	1 481 728	1 647 016

Year	2039	2040	2041	2042	2043	2044
Newly rewetted area (ha)	172 618	179 948	187 277	194 607	201 937	216 597
Cumulative rewetted area (ha)	1 819 634	1 999 581	2 186 859	2 381 466	2 583 403	2 800 000

The estimate for a rewetting payment is based on the opportunity cost of rewetting. Opportunity costs can be considered in both the short- and long-term, as not all costs associated with drained agricultural peatland use can be escaped immediately after rewetting (e.g., fixed cost of agricultural buildings). We approximate the rewetting payment based on the short-term opportunity costs, to cover all the costs comprehensively in the beginning of the rewetting process.

We first calculate the long-term opportunity costs based on land rents for the respective area. The data derivation method corresponds to the approach in Annex Chapter 6. In addition to the data for arable land, we calculate the following EU ratio for grassland:

EU ratio for grassland= five-year average of grassland rents/(five-year average of arable land rents + grassland rents) = 0.66.

When using data on land rents from the Farm Accountancy Data Network (FADN), for grassland we use the farm type (6) Other grazing livestock (49) Specialist cattle.

Per NUTS-2 region, the land rents for arable land and grassland are multiplied by the hectares of rewetted peatland formerly used as arable land and grassland, respectively. The results of all NUTS-2 regions are summed up and divided by the total rewetted peatland area in the EU. The resulting 278 euro per hectare are used as the EU weighted average long-term opportunity cost of rewetting.

Second, to obtain the short-term opportunity cost, the long-term opportunity costs are multiplied by a factor of 2 to 4 based on the findings of Domke (2023) for Germany. This factor reflects the observed differences between long- and short-term opportunity costs in Germany. This results in a range of 556 to 1 112 euro per hectare for the short-term opportunity cost, with a mean of 834 euro per hectare, which we use as an annual peatland rewetting payment.

We consider the annual payment to be constant and paid to the full amount from 2025 until 2035, and then phased out linearly after 2035 (Table A30).

Annual rewetting payment between 2025 and 2045

→ Table A30

Year	2025–2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Payment (euro per ha)	834	751	667	584	500	417	334	250	167	83	–

8 Forest management (Chapter 4.7)

8.1 Potential additional forest harvest from adaptation measures to climate change

We calculate the potential additional harvest at EU level that could result from large-scale adaptation measures implemented each year. This allows us to determine the additional volume of wood that could potentially be brought to market. Our calculation indicates that adaptation measures could generate an additional 25 to 100 million cubic meters (m^3) of harvest at EU level, representing a 5 to 20% increase compared to the 2020 harvest from forests.

Short method description

We derive the potential additional harvest from the forest area estimated for adaptation, the average growing stock per hectare and two different harvest scenarios: a) an intensive approach, mainly based on clear cuts (80% of the area is harvested through clear-cutting) and b) an extensive approach, where only 20% of the area is harvested through clear-cutting.

Data

To define the adapted forest area per year, we assume that half of the total area potentially requiring adaptation is converted between 2025 and 2045. This amounts to roughly one-third of the EU forests (Hickler et al. 2012, Hinze et al. 2023). The total forest area in the EU is 160 million hectares (Eurostat 2023c); this results in 27 million hectares of actively adapted forests between 2025 and 2045, or 1.3 million hectares per year on average. We calculate with the EU average growing stock of 173 m^3 per hectare for 2020 (FAO 2020).

Calculation

We calculate the volumes of wood generated by the adaptation of 1.3 million hectares in the two scenarios described above. We apply two different substitution rates to theses volumes which represent the proportion of the adaptation-generated harvest that replaces the harvest which would have occurred without adaptation programmes: 40% in the intensive scenario and 60% in the extensive scenario. This calculation allows us to determine the additional volume of wood that could potentially be introduced to the market due to these adaptation measures.

8.2 Area needed for the 10% reduction of the forest harvest

To achieve a 10% reduction in EU forest harvest, we calculate the area of stable forests where harvesting would be postponed. Depending on the intensity assumed for the postponed harvests, this area ranges from 310 000 to 380 000 hectares per year. Over a 20-year period, this amounts to approximately 6.3 to 7.5 million hectares, or roughly 5% of the EU's forests.

Short method description

We assume that harvest is postponed for a 20-year period in the respective forest area. We derive a postponed harvest per hectare from the average growing stock per hectare for two different levels of harvest. With this postponed harvest per hectare, we calculate the area needed to reach the 49 million m^3 harvest reduction per year.

Data

We calculate on the basis of the EU average growing stock per hectare (FAO 2020) and the EU forest area (Eurostat 2023c). The forest harvest for 2020 is calculated using a trend of the period 2013-2017 based on the 2021 EU wood resource balance (last year reported: 2017) as it contains detailed data on the use of wood (European Commission 2021). The calculated harvest for 2020 is about 490 million m^3, which is very close to the Eurostat statistic for the 2020 harvest of 482 million m^3 (Eurostat 2023g).

Calculation

We define two intensity levels of harvest, the first one combining intensive and extensive harvests and the second one being only intensive. The avoided harvest amounts to 117 m^3 per hectare in the first case and 138 m^3 per hectare in the second. This translates into 380 000 hectares and 310 000 hectares of forests where harvest must be postponed to achieve a 10% reduction in EU forest harvest. The area needed is higher if shorter commitment periods are assumed and lower if the measures are applied on stands with growing stocks higher than the European average.

8.3 CO_2 removal potential from reduced forest harvest

We estimate the additional carbon dioxide (CO_2) sequestration in EU forests that can be expected from a 10% reduction in EU forest harvesting. We calculate an annual removal of 30 million tonnes of CO_2 ($MtCO_2$) for the period 2020–2045, which represents roughly 10% of the 2020 level of sequestration by forests in the EU (EEA 2022).

Short method description

We assume a 10% reduction of the annual EU forest harvest compared to 2020 and use the Carbon Balance Indicator (CBI) to calculate the CO_2 sequestration gains of this harvest reduction. The CBI is an estimate of the impact of wood harvest on forest carbon stocks and can be interpreted as carbon opportunity costs of harvest (Soimakallio et al. 2022).

Data

The harvest reduction is assumed at 49 million m^3, as described in Annex Chapter 8.2. The average CBI value of 1.43 (short-term, 1-30 years) is taken from Soimakallio et al. (2022). This study also assumes an average carbon content of wood of 0.2 tonnes carbon per m^3.

We adopt a conservative approach by:

- Assuming that 40% of the non-harvested biomass could have fed the Harvested Wood Product (HWP) pool and applying therefore a reduction of 0.4 to the CBI,
- Introducing an additional reduction factor 0.8 to account for the lower growth in the Mediterranean forests as the 1.43 value covers only temperate and boreal forests.

Calculation

The CO_2 sequestration is calculated by multiplying the 10% harvest reduction of 49 million m^3 with:

- An average CBI of 1.43 minus 0.4 for the non-harvested wood that, if harvested, could have been added to the HWP pool,
- A carbon content of 0.2 tonnes C/m^3,
- The conversion factor from C to CO_2 of 44/12,
- A reduction factor of 0.8 to account for the lower growth in the Mediterranean forests.

8.4 CO_2 removal potential from afforestation

We estimate the additional CO_2 sequestration from the afforestation of 5 million hectares at EU level. We calculate an annual average removal of 11 $MtCO_2$ for the period 2025–2045 and an additional removal of 20 $MtCO_2$ in new forests for the year 2045. Areas for afforestation are introduced exogenously into the land balance of CAPRI to ensure consistency of land use.

Short method description

Additional sequestration from afforestation can be calculated by multiplying the afforestation area of 5 million hectares with the Emission Factors (EFs) for the aboveground and belowground biomass provided by the Intergovernmental Panel on Climate Change (IPCC). A conservative approach is adopted by excluding the litter carbon pool as it is assumed to be unstable as well as the deadwood carbon pool, as it is assumed to be limited on afforestation areas in the first decades. We assume a linear growth of the newly afforested area starting from 2025 and until 2045 and that the entire afforested area is established on arable land.

Data

We apply the emission factors of the IPCC of 1.37 tonnes of carbon per hectare per year for the Aboveground Biomass (AGB) and 0.26 tonnes of carbon per hectare per year for the Belowground Biomass (BGB) (IPCC 2019). The belowground biomass is derived by using the IPCC's root-to-shoot factor of 19.2%.

Regarding land use change, IPCC does not provide figures on carbon stocks of annual crops, as they are considered planted and harvested in the same year. The soil carbon sequestration rate of the afforested areas is derived from Paul et al. (2009) who estimate a sequestration rate of 1.4 tonnes carbon per hectare per year.

Calculation

The CO_2 sequestration potential for the different pools (AGB, BGB and soil carbon) is the result of multiplying the afforested area per year with the above-mentioned EFs.

The CO_2 removal potential of the new afforested area in 2045 is the following:
- About 20.7 $MtCO_2$ in AGB,
- About 3.3 $MtCO_2$ in BGB,
- About 2.6 $MtCO_2$ in soils.

To get a conservative estimate, we apply a 25% precautionary reduction. The resulting CO_2 removal potential of the afforestation measure of our scenario is thus estimated at around 20 $MtCO_2$ for the year 2045. This amount is expected to continue increasing well after 2045 if the technical choices made for afforestation, in particular the tree species and the reproduction material, allow for growth under the new climatic conditions.

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