European Commission

JRC TECHNICAL REPORT

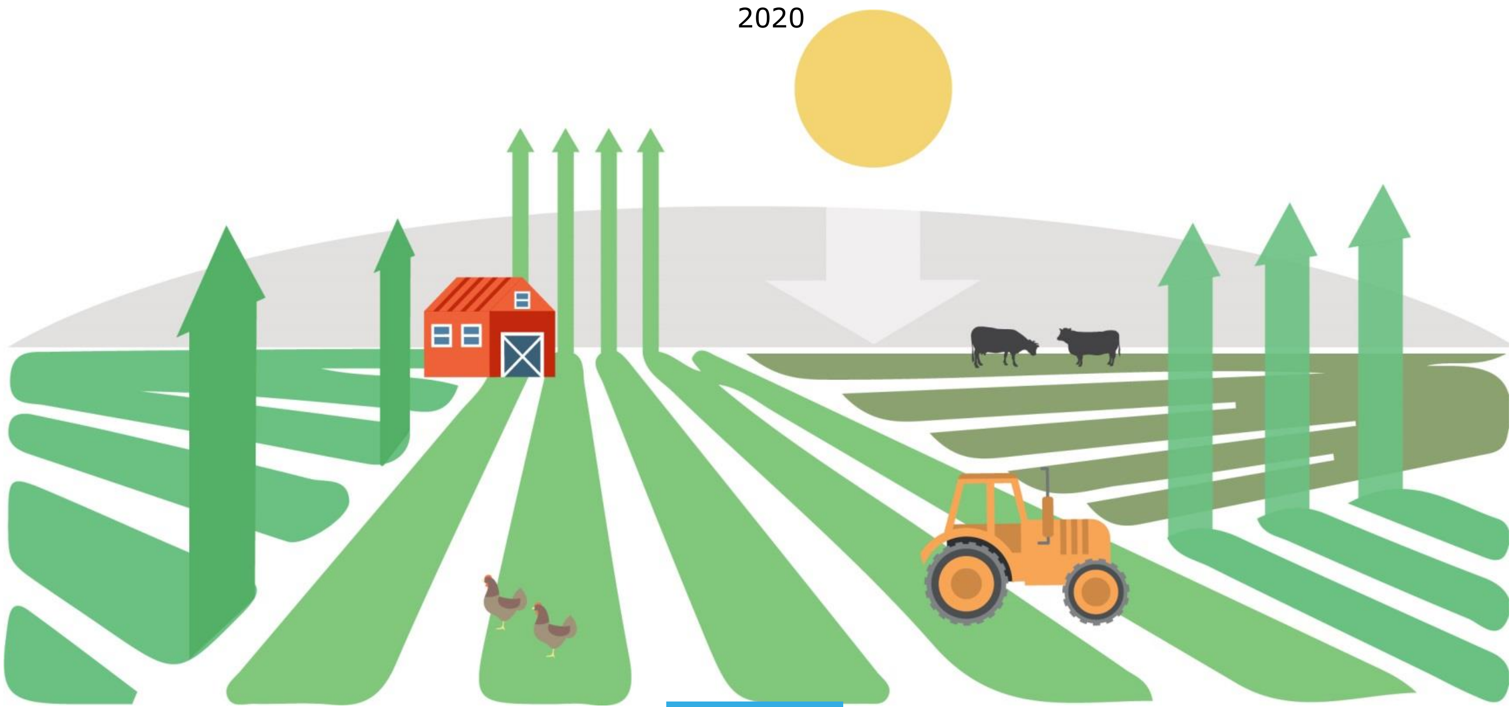
Economic assessment of GHG mitigation policy options for EU agriculture:

A closer look at mitigation options and regional mitigation costs - EcAMPA 3

Ignacio Pérez Domínguez, Thomas Fellmann, Peter Witzke, Franz Weiss, Jordan Hristov, Mihaly Himics, Jesús Barreiro-Hurlé, Manuel Gómez-Barbero and Adrian Leip

Editor: Thomas Fellmann

2020



Joint Research Centre

EUR 30164 EN

Contact information
Address: European Commission, Joint Research Centre, Edificio Expo. c/ Inca Garcilaso, 3. 41092 Seville (Spain)
Email: JRC-D4-Secretariat@ec.europa.eu
Tel.: +34 954488318

EU Science Hub
https://ec.europa.eu/jrc

JRC120355

EUR 30164 EN

PDF	ISBN 978-92-76-17854-5	ISSN 1831-9424	doi:10.2760/4668
Print	ISBN 978-92-76-17855-2	ISSN 1018-5593	doi:10.2760/552529

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Pérez Domínguez I., Fellmann T., Witzke P., Weiss F., Hristov J., Himics M., Barreiro-Hurle J., Gómez Barbero M., Leip A., *Economic assessment of GHG mitigation policy options for EU agriculture: A closer look at mitigation options and regional mitigation costs (EcAMPA 3)*, EUR 30164 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-17854-5, doi:10.2760/4668, JRC120355

Contents

Abstract

This report highlights the importance of assessing emission mitigation from a multi-dimensional perspective. For this, a quantitative framework to analyse the potential contribution of different technological mitigation options in EU agriculture is described in this report. Within the boundaries of the analysis, the need to consider land use, land-use change and forestry emissions and removals for a comprehensive analysis of the sector's potential contribution to achieve certain greenhouse gas mitigation targets is highlighted. The assessment of carbon dioxide emissions and removals is also important in light of the new flexibility introduced in the EU 2030 regulation framework. Regarding a possible ranking of mitigation technologies in terms of their mitigation potential and attached costs, the analysis clearly highlights the need to consider mitigation technologies as 'a bundle'. It is important to avoid the simple aggregation of mitigation potentials by single measures without taking into account their interactions both from a biophysical and economic perspective. Moreover, the analysis quantifies how mitigation measures might influence differently the agricultural sector in different EU Member States, stating that there is no 'one fits all' rule that could be followed for selecting which mitigation technologies should be implemented at regional level. In the policy context of the European Green Deal, the Effort Sharing Regulation and the CAP-post 2020, our results imply that farmers should have flexibility with regard to which mitigation options to adopt in order to find the right mix fitting to the regional circumstances.

Keywords: EU agriculture, climate change mitigation, technologies, land use and land use change, marginal abatement cost curves

1 Introduction

The 2030 EU energy and climate framework includes EU-wide targets and policy objectives for the period from 2021 to 2030. One of the key targets is the reduction of greenhouse gas (GHG) emissions by at least 40% below 1990 levels by 2030. To achieve this target, several legislative actions were approved at EU level, affecting both the sectors under the EU emissions trading system (ETS) and the rest of non-ETS sectors, which will need to cut emissions by 43% and 30%, respectively, compared to 2005. For non-ETS sectors, such as agriculture, transport, buildings and waste, the new EU Effort Sharing Regulation establishes binding annual GHG emission targets for EU Member States (MS). This Regulation (EU) 2018/842, adopted in May 2018, provides new flexibility as it allows to access credits from the land use sector. The aim of this new flexibility is to stimulate additional action in the land use sector by allowing MS to use up to 280 million credits over the entire period 2021-2030 to comply with their national targets. If needed, all MS are eligible to make use of this flexibility, but access is higher for those MS with a larger share of emissions from agriculture. According to the regulation, this flexibility is supposed to acknowledge both the lower mitigation potential of the agriculture and land use sectors, and an appropriate contribution of the sectors to GHG mitigation and sequestration (Council of the European Union 2018a). Specific accounting rules on GHG emissions and removals related to land use, land-use change and forestry ('LULUCF') are set out in the Regulation (EU) 2018/841 (Council of the European Union 2018b). Considering the aforementioned flexibility, MS have to ensure that net emissions from LULUCF are compensated by an equivalent removal of CO_2 from the atmosphere through action in the sector, which is known as the 'no debit' rule.

The above-mentioned regulatory framework implements the agreement of EU leaders in October 2014 that all sectors should contribute to the EU's 2030 GHG emission reduction target, including agriculture and the LULUCF sectors. Accordingly, the sectors' GHG emissions mitigation potential needs to be assessed, as well as the costs for and possible impacts on agriculture, forestry and other land use (AFOLU). Within the context of the policy discussions of the integration of the agricultural sector into the EU 2030 policy framework for climate and energy, the JRC launched the project "Economic assessment of GHG mitigation policy options for EU agriculture" (EcAMPA). The first report of EcAMPA was published by Van Doorslaer et al. (2015), followed by EcAMPA 2 (Pérez Domínguez et al. 2016)[1]. The modelling tool used for the EcAMPA studies is the Common Agricultural Policy Regional Impact Analysis (CAPRI) model (www.capri-model.org). A key contribution in the framework of the EcAMPA project so far was the implementation of specific endogenous GHG mitigation technologies in the CAPRI model, tested in several illustrative GHG mitigation policy scenarios. The methodology, however, needed further refinements regarding the representation of mitigation technologies. Furthermore, agricultural carbon dioxide (CO_2) emissions (and sinks) related to the LULUCF sector had to be incorporated into the analysis (with regard to both accounting and technological mitigation options) to enable the assessment of LULUCF-related CO_2 emissions and removals. These issues are tackled within the EcAMPA 3 study.

Building on the experience of EcAMPA 1 and EcAMPA 2, the general objectives of EcAMPA 3 were to further improve the CAPRI modelling system regarding the representation of GHG emissions mitigation technologies, completely integrate the accounting of agricultural carbon dioxide (CO_2) emissions and removals related to agriculture and the LULUCF sectors, and to apply the model to test and analyse the potential of technological mitigation measures individually and together. The specific objectives of the project were:

1. Full incorporation of a module accounting for LULUCF-related CO_2 emissions and removals linked to agricultural production in the EU, and testing the possibility of CO_2 accounting for non-EU regions based on CAPRI simulations.

([1]) Please note the contribution of EcAMPA 2 during the impact assessment phase of the Regulation (EU) 2018/841 (European Commission 2016b)

2. Integration of the technological mitigation options for CO_2 mitigation in agriculture, and improvement of underlying assumptions used for calibration and parameter specification of some non-CO_2 mitigation technologies.
3. Testing and analysis of each technological mitigation measure individually and together, and calculation of marginal abatement cost curves specific to mitigation technologies and regions.

The main difference compared to previous EcAMPA studies is the technical nature of EcAMPA 3, i.e. the focus is mainly on methodological developments for a better representation of mitigation technologies in CAPRI, and testing and analysing the mitigation potential and related costs. Therefore, the scenarios in this report are 'technical', i.e. only designed to test the (theoretical) maximum mitigation potential of each technological option following the modelling approach and the assumptions made in CAPRI. Moreover, we put the level of emissions mitigation achieved by the technological options into perspective with respect to the associated costs by analysing the marginal abatement costs (MACs) of each option. For the analysis and representation we present marginal abatement cost curves (MACCs), following first a 'standalone measures' and then a 'combined measures' approach.

For EcAMPA 3 the emission accounting in CAPRI was updated, using the global warming potential (GWP) of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), i.e. 25 and 298 for methane and nitrous oxide, respectively. It has to be further noted that the analysis was conducted before Brexit and, therefore, the presented results include the UK and the aggregated results represent the EU-28.

The report is structured as follows: Chapter 2 provides an overview of GHG emissions accounting in CAPRI, covering both non-CO_2 emissions and the newly developed approach for CO_2 emissions. The technological GHG emissions mitigation options covered in this report are presented in Chapter 3 along with the major assumptions and the CAPRI modelling approach for costs and uptake of mitigation technologies. Chapter 4 presents the test and analysis of each of the mitigation technologies, and in Chapter 5 the level of emissions mitigation achieved by the technological options is put into perspective with respect to the associated costs by presenting and analysing MACCs. Chapter 6 presents a discussion of the findings and draws conclusions.

2 GHG emissions accounting in CAPRI

This chapter first provides some general information on the CAPRI modelling system (section 2.1). So far, CAPRI only covered agricultural non-CO_2 GHG emissions (i.e. methane and nitrous oxide), and section 2.2 provides a brief overview on the respective emission accounting. One of the major developments in EcAMPA 3 was the incorporation of the accounting of CO_2 emissions and removals in CAPRI. Section 2.3 outlines the new model developments related to the full incorporation of a carbon cycle model for EU agriculture and a module for accounting of CO_2 effects linked to agricultural production. Section 2.4 presents a summary and overview of EU GHG emissions in the reporting sectors 'agriculture' and 'LULUCF' covered in CAPRI.

2.1 The CAPRI modelling system

CAPRI is an economic large-scale comparative static, partial equilibrium model focusing on agricultural commodity markets and some primary processing sectors (oilseeds, dairy, biofuels). The model interlinks highly detailed and disaggregated models of EU regional agricultural supply to a global market model for agricultural commodities. The regional supply models simulate the profit maximizing behaviour of representative farms for all EU regions[2] with explicit calibration to observed market developments by means of Positive Mathematical Programming (PMP) methods. The supply module consists of about 280 independent aggregate optimisation models, representing regional agricultural production activities (i.e. 28 crop and 13 animal activities) at NUTS 2 level within the EU-28. These models combine a Leontief technology for intermediate inputs covering low- and high-yield variants for the different production activities, with a non-linear cost function that captures the effects of labour and capital on farmers' decisions. In addition, constraints relating to land availability, nutrient balances and policy restrictions are taken into account. The cost function used allows for calibration of the regional supply models and a smooth simulation response. The market module consists of a spatial, global multi-commodity model for about 60 primary and processed agricultural products, covering about 80 countries in 40 trading blocks. International trade, covering bilateral trade flows, and price transmission between agricultural commodity markets (and biofuels) are modelled based on the Armington assumption of quality differentiation. Supply, feed, processing and human consumption functions in the market module ensure full compliance with micro-economic theory. The link between the supply and market modules is based on an iterative procedure (Britz and Witzke 2014).

CAPRI is frequently used for the impact assessment of agricultural, environmental, and trade related issues, like, for example, the expiry of the EU milk quota (Witzke et al. 2009) and sugar quota systems (Burrell et al. 2014), possible EU trade agreements (Burrell et al. 2011), Common Agricultural Policy (CAP) greening measures (Gocht et al. 2017) and possible future pathways for the CAP (M'barek et al. 2017). Moreover, CAPRI is used for the analysis of climate change impacts on EU agriculture (Shrestha et al. 2013; Blanco et al. 2017; Pérez Domínguez and Fellmann 2018), and climate change mitigation in the agricultural sector in the EU (Pérez Domínguez et al. 2016; Fellmann et al. 2018; Himics et al. 2018, 2020) and at global level (Hasegawa et al. 2018; van Meijl et al. 2018; Frank et al. 2019).

2.2 Accounting of non-CO2 emissions in CAPRI

The general CAPRI approach for the accounting of agricultural non-CO_2 emissions, i.e. methane and nitrous oxide emissions is explained in detail in previous publications (Van Doorslaer et al. 2015; Pérez Domínguez et al. 2016; Fellmann et al. 2018) and has not changed for the EcAMPA 3 study. Therefore, this section provides only a brief summary on the accounting of non-CO_2 emissions in CAPRI.

([2]) CAPRI uses NUTS 2 (Nomenclature of Territorial Units for Statistics, from Eurostat) as the regional level of disaggregation.

CAPRI captures the links between agricultural production activities in detail (e.g. food/feed supply and demand interactions or animal production cycle) and, based on the production activities, inputs and outputs define agricultural GHG emission effects. The CAPRI model incorporates a detailed nutrient flow model per agricultural activity and region, which includes explicit feeding and fertilising practices (i.e. the balancing of nutrient needs and availability) and calculates yields per agricultural activity. With this information, CAPRI quantifies GHG emissions following the IPCC guidelines (IPCC 2006). The IPCC provides various methods for calculating a given emission flow. All methods use the same general structure, but the level of detail for the calculation of emission flows can vary. These IPCC methods are differentiated into 'Tiers', using an increasing level of activity, technology and regional detail. Tier 1 methods are generally calculated by multiplying an activity by a default emission factor, and hence require fewer data and less expertise than the more advanced Tier 2 and Tier 3 methods. Tier 2 and Tier 3 methods have higher levels of complexity and require more detailed country-specific information on, for example, management or livestock characteristics. In CAPRI, a Tier 2 approach is generally used for the calculation of emissions. For emission sources for which the necessary underlying information is missing, a Tier 1 approach is used (e.g. rice cultivation). A more detailed description of the general calculation of agricultural emission inventories on activity level in CAPRI (without the inclusion of technological mitigation options) is given in Pérez Domínguez (2006), Leip et al. (2010) and Pérez Domínguez (2012). The reporting of non-CO_2 emissions in the EcAMPA 3 report mimics the reporting on emissions by the EU to the United Nations Framework Convention on Climate Change (UNFCCC), using the global warming potential (GWP) of the IPCC Fourth Assessment Report (AR4), i.e. 25 and 298 for methane and nitrous oxide, respectively.

2.3 Accounting of CO_2 emissions in CAPRI

One of the main challenges in EcAMPA 3 relates to the calculation of CO_2 emissions linked to agricultural production in CAPRI and the identification and integration of the most relevant technological mitigation options regarding CO_2 mitigation in agriculture. In this section the model developments related to the incorporation of (i) a carbon cycle model for EU agriculture (sections 2.3.1 and 2.3.2), and (ii) a module for accounting of CO_2 effects linked to agricultural production in CAPRI (sections 2.3.3 and 2.3.4) are described.

2.3.1 Carbon cycle model for EU agriculture

An agricultural carbon cycle model quantifies all relevant carbon flows related to both livestock and crop production processes (cf. Figure 1). It is important to note, that it does not include carbon flows and CO_2 emissions from land use changes (LUC).

In CAPRI, so far the following carbon flows related to animal production and crop production activities are included (Weiss and Leip 2016):

- Feed intake in livestock production (C)
- Carbon retention in livestock and animal products (C)
- Methane emissions from enteric fermentation in livestock production (CH_4)
- Animal respiration in livestock production (CO_2)
- Carbon excretion by livestock (C)
- Regional manure imports and exports (C)
- Methane emissions from manure management in livestock production (CH_4)
- Carbon dioxide emissions from manure management in livestock production (CO_2)
- Runoff from housing and storage in livestock production (C)
- Manure input to soils from grazing animals and manure application (C)
- Carbon input from crop residues (C)

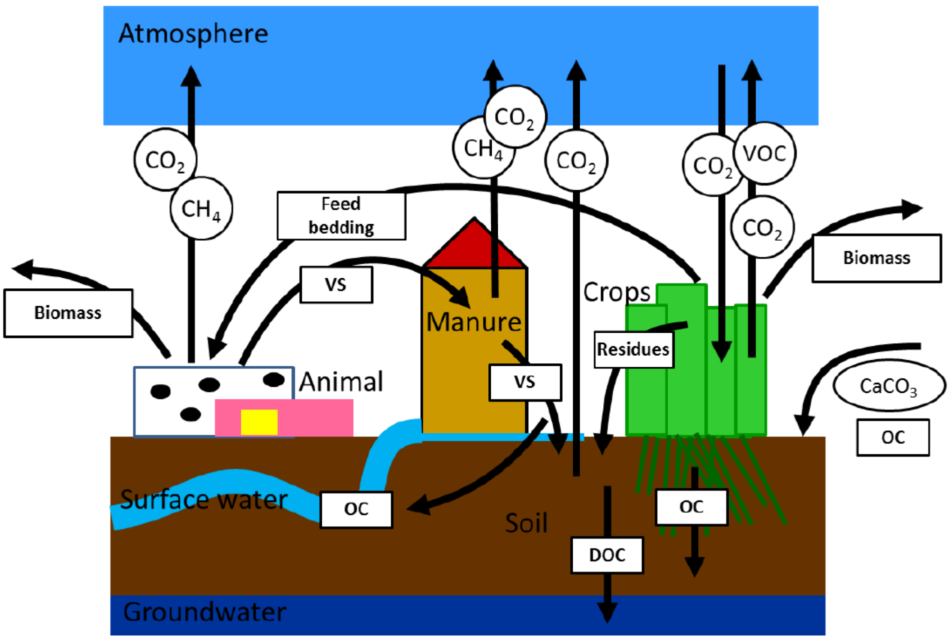
- Carbon export by crop products (C)
- Carbon dioxide emissions from the cultivation of organic soils (CO_2)
- Carbon dioxide emissions from liming (CO_2)
- Runoff from soils (C)
- Methane emissions from rice production (CH_4)
- Carbon sequestration in soils (C)
- Carbon losses from soil erosion (C)
- Carbon dioxide emissions from soil and root respiration (CO_2)

Accordingly, CAPRI does not consider the following carbon flows:

- Volatile organic carbon (VOC) losses from manure management (C)
- Carbon losses from leaching (C)
- Carbon dioxide emissions from urea application (CO_2)

The VOC losses (non-CH_4) from manure management are small and can be neglected. Carbon losses from leaching can be a substantial part of carbon losses from agricultural soils (e.g. Kindler et al. 2011). Although they are not yet specifically quantified in the CAPRI approach, they are not neglected but put together with soil respiration in one residual value in the CAPRI carbon balance. CO_2 emissions from urea application account for about 1% of total GHG emissions in the agriculture sector, but are not yet included in the CAPRI carbon cycle model.

Figure 1. Carbon flows in the agricultural production process



Note: CO2 = carbon dioxide; CH4 = methane; VOC = volatile organic carbon VS= volatile solids; DOC = dissolved organic carbon; OC= organic carbon; CaCO3 = calcium carbonate

Source: Weiss and Leip (2016)

In the following, we briefly describe the general methodology for the quantification of the carbon flows that are taken into account in the CAPRI approach.

2.3.2 General methodology for the quantification of carbon flows (emissions and removals)

– *Feed intake in livestock production*

Feed intake is determined endogenously in CAPRI based on livestock nutrient and energy needs. The carbon content of feedstuff is derived from the combined information on carbon contents of amino acids and fatty acids, the shares of amino acids and fatty acids in crude protein and fats of different feedstuffs, and the respective shares of crude protein, fats and carbohydrates. For carbohydrates, we assume a carbon content of 44%. Data was obtained from Sauvant et al. (2004) and from National Research Council (2001).

– *Carbon retention in livestock and animal products*

Similar to feed intake, we can quantify the carbon stored in living animals using the above-mentioned data for animal products. The values for meat are multiplied with the animal specific relation of live weight to carcass. For simplification, the fact that bones or skins etc. may have different carbon contents than meat is ignored.

– *Methane emissions from enteric fermentation*

Methane emissions from enteric fermentation are calculated endogenously in CAPRI based on a Tier 2 approach following the IPCC guidelines (IPCC 2006, cf. section 2.2).

– *Animal respiration in livestock production*

Intake of carbon is a source of energy for the animals. CAPRI calculates the gross energy intake on the basis of feed intake as described above. However, not all carbon is 'digestible' and hence can be transformed into biomass or respired. Digestibility of feed (for cattle activities) is calculated on the basis of the National Research Council (2001) methodology. Non-digestible energy (or carbon) is excreted in manure (see below), while the 'net energy intake' refers to the equivalent to the energy stored in body tissue and products plus losses through respiration and methane.

According to Madsen et al. (2010) the heat production per litre of CO_2 is 28 kJ for fat, 24 kJ for protein and 21 kJ for carbohydrates. Using a factor of 1.98 kg/m3 for CO_2 (under normal pressure) or 505.82 l/kg we get 14.16 MJ/kg CO_2 for fat, 12.14 MJ/kg CO_2 for protein and 10.62 MJ/kg CO_2 for carbohydrates, which translates into 0.071, 0.082 and 0.094 kg CO_2 per MJ, respectively. These values are used to get the carbon directly from net energy intake (for each feedstuff), which is an endogenous variable in CAPRI depending on the feed intake. From this we subtract the carbon retained in living animals and in animal products and the methane emissions from enteric fermentation in order to compute the carbon respiration from livestock.

– *Carbon excretion by livestock*

Carbon excretion is defined as the difference between the carbon intake via feed, the retention in livestock and the emissions as carbon dioxide (respiration) and methane (enteric fermentation):

(1) C excretion = Feed intake – retention – emissions (CO_2, CH_4)

Carbon excretion can, therefore, be determined as the balance between the positions 1-4. As carbon retention plus emissions by default gives the net energy intake (see above), this is equivalent to

(2) C excretion = C from gross energy intake – C in net energy intake

– *Regional manure imports and exports*

Manure available in a region may not just come from animal's excretion in the region but could also be imported from other regions, while, conversely, manure excreted may be exported to another region. CAPRI calculates the net manure trade within regions of the same MS, and this has to be accounted in the carbon balance as a separate position. For simplification, the model assigns the emissions of all manure excreted to the exporting region, while the carbon and nutrients are assigned to the importing region.

– *Methane emissions from manure management in livestock production*

Once the carbon is excreted in form of manure (faeces or urine), it will either end up in a storage system or it is directly deposited on soils by grazing animals. Depending on temperature and the type of storage, part of the carbon is emitted as methane. These emissions are quantified in CAPRI following a Tier 2 approach (cf. section 2.2), using shares of grazing and storage systems from the GAINS database (for more explanation see also Leip et al. 2010).

– *Carbon dioxide emissions from manure management in livestock production*

During storage or grazing, carbon is not only emitted in form of methane, but part of the organic material is mineralized and carbon released as carbon dioxide. Following the FarmAC model[3], we assume a constant relation between carbon emitted as methane and total carbon emissions (methane plus carbon dioxide) of 63%. Therefore, the carbon loss through carbon dioxide emissions can be quantified as:

(3) $C\ (CO_2) = C(CH_4) * 0.37/0.63$

– *Runoff from housing and storage in livestock production*

Part of the carbon excreted by animals is lost via runoff during the phase of housing and storage. We assume the share to be equivalent to the share of nitrogen lost via runoff. In CAPRI we use the shares from the Miterra-Europe project, which are differentiated by NUTS 2 regions (for more information see Leip et al. 2010).

– *Manure input to soils from grazing animals and manure application*

Carbon from manure excretion minus the emissions from manure management and runoff during housing and storage, corrected by the net import of manure to the region, is applied to soils or deposited by grazing animals. Other uses related to manure (e.g. trading, burning, etc.) are so far not considered in CAPRI. Moreover, we add here the carbon from straw from cereal production not fed to animals, assuming that all harvested straw (endogenous in CAPRI) not used as feedstuff is used for bedding in housing systems. The carbon content from straw is quantified in the same way as for feedstuff (see above). In contrast, other cop residues are treated under the position "carbon inputs from crop residues". Bedding materials coming from other sectors are currently ignored.

– *Carbon input from crop residues*

The dry matter from crop residues is quantified endogenously in CAPRI following the IPCC guidelines (IPCC, 2006; crop specific factors for above and below ground residues related to the crop yield). For the carbon content, a unique factor of 40% is applied as the information used for feed intake is generally only available for the commercially used part of the plants, but not specified for crop residues.

– *Carbon export by crop products*

Carbon exports by crop products are calculated as described above for 'feed intake', using the composition of fat and proteins by fatty and amino acids and the respective shares of these basic nutrients in the dry matter of crops.

([3]) The FarmAC model simulates the flows of carbon and nitrogen on arable and livestock farms, enabling the quantification of GHG emissions, soil C sequestration and N losses to the environment (for more information see: www.farmac.dk).

– *Carbon fixation via photosynthesis of plants*

Photosynthesis is the major source of carbon for a farm. Carbon is incorporated in plant biomass as sugar and derived molecules to store solar energy. Some of these molecules are 'exudated' by the roots into the soil. They provide an energy source for the soil microorganisms – in exchange to nutrients. In the current version of CAPRI, we assume that 100% of the photosynthetic carbon not stored in harvested plant material or crop residues, returns 'immediately' to the atmosphere as CO_2 (root respiration) and has therefore no climate relevance. Accordingly, the effective fixation of carbon via photosynthesis is assumed to be equal to the exported carbon with crop products plus the carbon from crop residues. Therefore, it is not explicitly calculated.

– *Carbon dioxide emissions from the cultivation of organic soils*

Carbon dioxide emissions from the cultivation of organic soils are calculated by using shares of organic soils derived from agricultural land use maps for the year 2000. For details see Leip et al. (2010).

– *Carbon inputs from liming*

Agricultural lime is a soil additive made from pulverised limestone or chalk, and it is applied on soils mainly to ameliorate soil acidity. Total liming application on agricultural land as well as the related emission factor is taken from past UNFCCC notifications. A coefficient per ha is computed dividing the UNFCCC total amount by the Utilizable Agricultural Area (UAA) in the CAPRI database. This coefficient per ha is computed from the most recent data and maintained in ex-ante simulations. In the context of the carbon balance the CO_2 emissions are converted into C and become carbon input into the system. For the attribution of liming to an activity we use the same rate for all crops and a unique rate per hectare.

– *Carbon runoff from soils*

Similar to the calculation of C runoff from housing and storage in livestock production we assume that the share of carbon lost via runoff from soils is equivalent to the respective share of nitrogen lost. The respective shares are provided by the Miterra-Europe project (cf. Leip et al. 2010).

– *Methane emissions from rice production*

Methane emissions from rice production are relevant only in a few European regions and are quantified in CAPRI via a Tier 1 approach following the IPCC guidelines (IPCC 2006, cf. section 2.2).

– *Carbon sequestration in soils*

Finally, we quantify the sequestered material after 20 years. The carbon change is based on simulations with the CENTURY agroecosystem model (Lugato et al. 2014) (aggregated from 1 km^2 to NUTS2 level), and calculated from the difference in the manure and crop residue input to soils between the simulation year and the base year. This is done because carbon sequestration is only achieved from an increased carbon input, assuming that the carbon balance in the base year is already in equilibrium. The total cumulative carbon increase is divided by 20, in order to spread the effect over a standardised number of years (consistent with the 2006 IPCC guidelines).[4]

([4]) The simulations with the CENTURY model were carried out by Emanuele Lugato from JRC.D3 in Ispra (for more details see Lugato et al. 2014).

– *Carbon losses from soil erosion*

Carbon losses from soil erosion are calculated on the basis of the Revised Universal Soil Loss Equation (RUSLE) model[5]. The equation has the following form:

(4) E = R * K * LS * C * P

Where

E: Annual average soil loss (t ha-1 yr-1),

R: Rainfall Erosivity factor (MJ mm ha-1 h-1 yr-1),

K: Soil Erodibility factor (t ha h ha-1 MJ-1 mm-1),

C: Cover-Management factor (dimensionless),

LS: Slope Length and Slope Steepness factor (dimensionless),

P: Support practices factor (dimensionless).

For more details on the factors used see Panagos et al. (2015).

In order to get the carbon loss we have to multiply with the carbon content of the soil. As approximation, we assume a 3% humus share for arable land and a 6% humus share for grassland. The carbon share in humus is around 2/3.

– *Carbon dioxide emissions from respiration of carbon inputs to soils*

Soil carbon losses are quantified as the residual between all carbon inputs to soils, the emissions and the carbon sequestered in the soils:

(5) Carbon losses via soil and root respiration =

Manure input from grazing and manure application

+ input from crop residues

- carbon losses (CH_4) from rice production

- carbon losses (CO_2) from the cultivation of organic soils

- carbon losses from runoff from soils

- carbon losses from soil erosion

- carbon sequestration in soils

Carbon losses from leaching should also be subtracted, but they are not specifically quantified in the CAPRI carbon cycle model so far. Therefore, the share of soil respiration is currently overestimated by the model.

2.3.3 Modelling land use and land use change emissions in the EU

The most important carbon effects from agriculture are related to both land use change and continued use of land, more specifically (i) effects related to deforestation and afforestation if influenced by agriculture; (ii) effects from land use changes (e.g. grassland to cropland and vice versa), and (iii) effects of continued land use in a specific category (cropland or grassland). A reliable estimation of these carbon effects from agriculture was the purpose of the development of the carbon cycle model (cf. section 2.3.1). For other land use types, like for example forest management (FM), CAPRI may only offer a far simpler treatment.

For the two types of carbon effects, from land use change and from (continued) land use, it is necessary to have a consistent estimation of the complete regional area balance (i.e. beyond agriculture) when solving the CAPRI regional supply models. This is achieved with the following elements:

(5) https://esdac.jrc.ec.europa.eu/themes/rusle2015

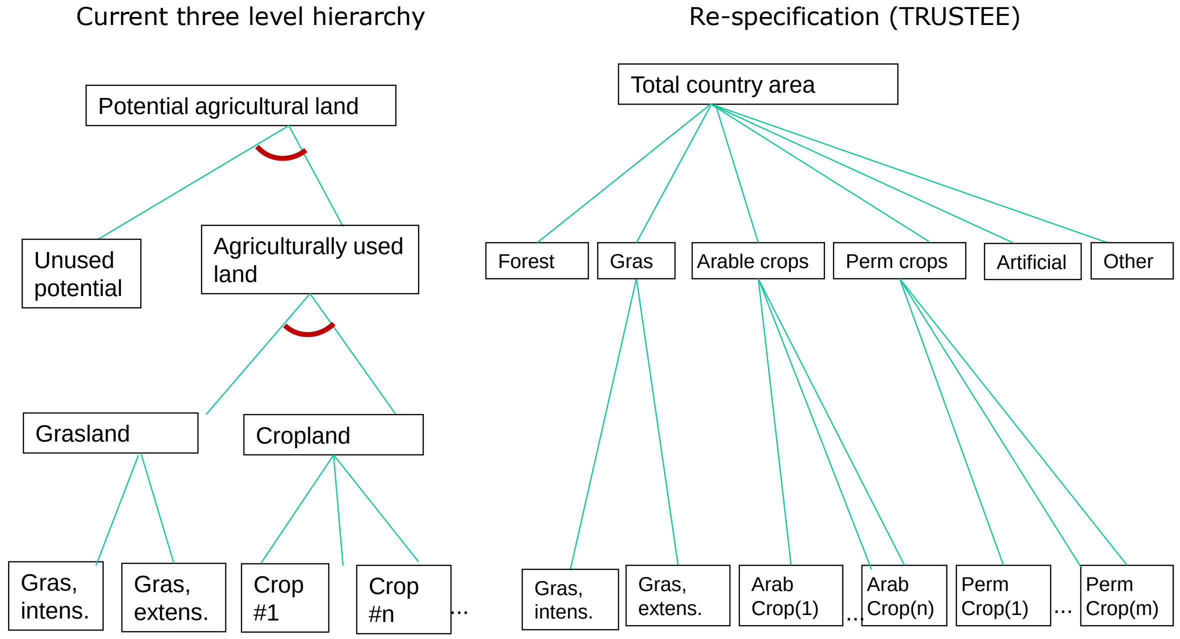
– An empirically estimated allocation system for the following land types: arable crops, perennials, pasture and meadows, forest, inland waters, artificial land and other land.

– A stochastic process specified according to historical data explaining the pattern of transitions between the basic UNFCCC land use categories.

The first element of the re-specification (complete area coverage) is graphically illustrated in Figure 2 (based on the TRUSTEE project[6]).

The land supply and transformation model developed within the TRUSTEE project is a bi-level optimisation model. At the higher level (depicted in the right part of the figure, sometimes referred to as the outer-problem), the economic agent decides how much land to allocate to each aggregate land use, based on the rents earned in each use and a set of parameters capturing the costs ensuring that the land is available to the intended use. At the lower level (sometimes referred to as the inner problem), the transitions between land classes are modelled, with the condition that the total land needs of the outer problem are satisfied. The inner problem is modelled as a stochastic process involving no explicit economic model. This means that we consider the structure of the land transition matrix to be shaped by natural conditions and suitability, as well as legal and habitual rules that are rather stable over time. The historical land transition data are thus used to determine the most likely values for transitions (i.e. the mode values), which would be reproduced if the simulated total changes of land classes were exactly matching the historical pattern. As this is never the case, the projected transitions need to deviate from the historical pattern, but should stay as close as possible to it. This inner problem optimisation is represented by adding the implied first order conditions for the maximisation of a Gamma density function to the constraints of the supply models[7].

Figure 2. Land use specification for modelling in CAPRI

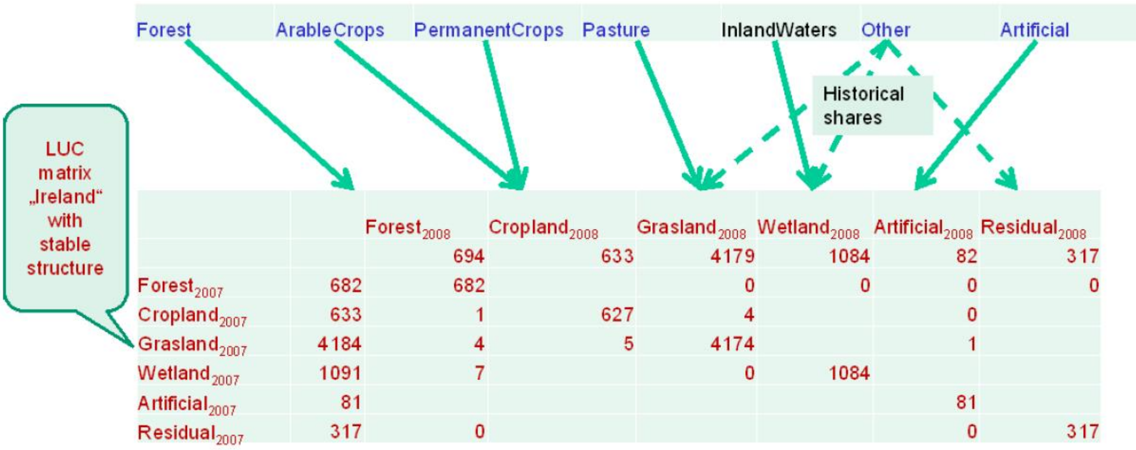


The development of this land supply and transformation model is complicated by the fact that land use classes in the CAPRI supply models are based on Eurostat classifications and, therefore, different from the ones in the UNFCCC accounting, which is the basis for the land use transition data set. In particular, Eurostat (or CORINE Land Cover) categories 'other land', 'inland waters' and 'pasture' are matching only imperfectly with their UNFCCC counterparts. To reconcile the differences, constant shares of the intersections of the

([6]) https://www.trustee-project.eu/
([7]) The same approach has been implemented under the SUPREMA project for non-European regions of CAPRI, see https://www.suprema-project.eu/images/SUPREMA-D23.pdf, section 3.2.1.2.

different sets are assumed, based on the historical data collected and consolidated in the CAPRI database (cf. Figure 3).

Figure 3. Example of mapping land use classes for Ireland with stable structure



		$Forest_{2008}$	$Cropland_{2008}$	$Grasland_{2008}$	$Wetland_{2008}$	$Artificial_{2008}$	$Residual_{2008}$
		694	633	4179	1084	82	317
$Forest_{2007}$	682	682		0	0	0	0
$Cropland_{2007}$	633	1	627	4		0	
$Grasland_{2007}$	4184	4	5	4174		1	
$Wetland_{2007}$	1091	7		0	1084		
$Artificial_{2007}$	81					81	
$Residual_{2007}$	317	0				0	317

It is important to note that the empirically estimated allocation system for the different land types is not yet operational in CAPRI and, therefore, the allocation of non-agricultural land use classes has been based on historical shares, similar to the current post-model reporting, but integrated into the supply models.

Note on the modelling of land use, land use change and forestry carbon effects

Similar to the approach for the carbon cycle model (see above), the carbon effects related to LULUCF are incorporated to the regional CAPRI supply models. In previous model versions these carbon effects were only calculated "post model", meaning after all other supply model results were already calculated. The incorporation into the regional supply models required the computation of relevant shares and per ha coefficients while solving the model.

2.3.4 Modelling land use and land use change emissions in non-EU regions

The ultimate goal of carbon accounting in the EU is to obtain a complete assessment of all GHG emission impacts related to EU agriculture and EU policies. Completeness includes also global repercussions and possible emission leakage effects from EU GHG abatement policies due to impacts in non-European regions.

Currently these leakage effects are estimated in the context of the product based emission accounting which may rely on computations done with the Aglink-Cosimo model based on FAO data for methane and nitrous oxide emissions. A similar accounting is used in CAPRI for CO_2 effects, but it suffers from some asymmetries in coverage (partly missing information on effects from conversion of grassland). Therefore, the carbon accounting to non-EU regions was extended relying basically on the same methodology used for EU regions (but without a carbon cycle module).

As with other tasks, the very first step to move into the direction of a carbon accounting in non-EU regions is the establishment of a suitable database to identify the land use changes between the six UNFCCC land use classes commonly used for the reporting. The data consolidation problem is in principle similar to parts of the CAPRI Complete and Consistent (COCO) database module for the EU regional supply models. It seems straightforward for industrialised non-European countries that offer UNFCCC notifications (USA, Australia, Japan, etc.), but it turned out that data conflicts are sometimes severe.

For example, FAO reports cropland to be about 48 million ha in Australia, whereas UNFCCC gives 35 million ha.

For developing countries, data on the key UNFCCC land categories, not to say evidence on land transitions, is very sparse. Complete land transition matrices have been found only for a few countries (Brazil, Democratic Republic of Congo, Indonesia, Malaysia, Papua New Guinea, Jamaica, and Ghana). Incomplete matrices are available for some additional countries, but these are more complicated to process. Consequently, missing prior values for land transitions for the majority of developing countries were estimated as a weighted average of complete transition matrices. The weighting formula considered both the similarity of land use shares in total area as well as geographical proximity.

Settlement areas (artificial area) were also missing for the majority of developing countries and, therefore, estimated. Amongst various alternatives, robust estimates for shares of urban areas in the total country area were obtained based on a regression on real GDP per ha of the country area. Intuitively, this captures both the income levels of countries as well as their land abundance. This permitted to single out the settlement area from the FAO aggregate "other land including settlements". The remaining area was subsequently allocated to grassland, wetlands and residual land according to the shares in similar countries, with "similarity" defined as for the land transitions.

It should be noted that the data compilation achieved so far for CAPRI advanced in terms of completeness, but this evidently means some compromise in terms of data quality. However, to prepare for the next steps of model development with global land use change monitoring during simulations, it appeared useful to advance with a complete database. The ultimate goal is to run GHG emission abatement scenarios that fully cover the entire land use sector, including non-CO_2 and CO_2 emissions in EU and non-EU regions simultaneously, and during the simulations (as opposed to post model calculation). For this goal there are still some elements missing:

1. Conversion of the current ad hoc approach for total area coverage (which is still focused on agriculture) to a land allocation system representing decision making of non-agricultural land owners. This is prepared already as a multinomial logit system in the context of the elasticity calibration but not yet fully tested.
2. Mapping from the "decision making area categories" like "fodder and fallow land" (FODFAL) to the six UNFCCC area classes, and including the land transitions between these classes.
3. Including the GHG accounting for CO_2 into the global market model of CAPRI.

Although these elements are still missing, the current EcAMPA 3 project has made important progress in view of this long-run CAPRI strategy[8].

([8]) The missing elements were addressed under the SUPREMA project, see https://www.suprema-project.eu/images/SUPREMA-D23.pdf, section 3.2.1.

2.3.5 Overview of EU agriculture and LULUCF emissions covered in CAPRI

Table 1 presents the emissions of the UNFCCC reporting sector 'agriculture' and the emission sources modelled in CAPRI. About 98.4% of the total EU GHG emissions officially reported to the UNFCCC in the category 'agriculture' are covered in CAPRI (cf. Figure 4).

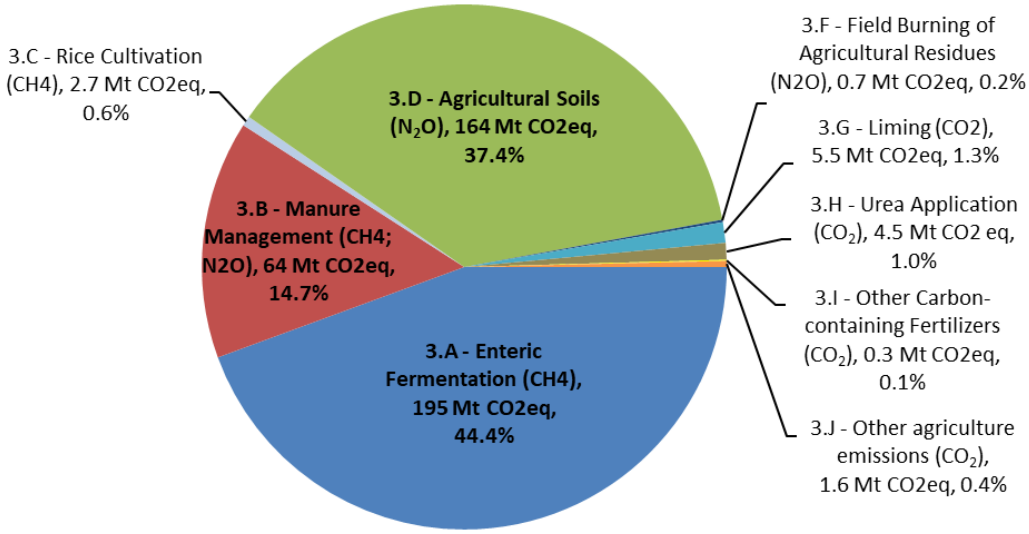
Table 1: Agriculture reporting items to the UNFCCC and emission sources modelled in CAPRI

	UNFCCC Reporting Sector Agriculture (CRF Sector 3)	CAPRI Reporting and modelling	
CH_4	A: Enteric fermentation	CH4ENT	Enteric fermentation
	B: Manure management	CH4MAN	Manure management
	C: Rice cultivation	CH4RIC	Rice cultivation
Nitrous oxide	B: Manure management	N2OMAN	Manure management (stable and storage)
	D: Agricultural soils		
	1. Direct N2O emissions from managed soils		
	1: Inorganic N fertilizers	N2OSYN	Synthetic fertilizer
	2: Organic N fertilizers	N2OAPP	Manure management (application)
	3: Urine and dung deposited by grazing animals	N2OGRA	Excretion on pasture
	4: Crop residues	N2OCRO	Crop residues
	5. Mineralization/immobilization associated with loss/gain of soil organic matter *		*Not active in the current version**
	6: Cultivation of histosols	N2OHIS	Histosols
	7. Other *		*Not covered in CAPRI**
	2. Indirect N2O emissions from managed soils		
	1: Atmospheric deposition	N2OAMM	Deposition of ammonia
	2: Nitrogen leaching and run-off	N2OLEA	Emissions due to leaching of nitrogen
	E: Prescribed burning of savannahs		*Not covered in CAPRI*
	F: Field burning of agricultural residues		*Not covered in CAPRI*
CO_2	G: Liming	CO2LIM	Liming
	H: Urea application		*Not covered in CAPRI*
	I: Other carbon-containing fertilizers		*Not covered in CAPRI*
	J: Other agriculture emissions		*Not covered in CAPRI*

Note: the inclusion of CO_2 emissions related to liming is new in EcAMPA 3 compared to previous model versions; * D.1.5 and D.1.7 are only about 0.6% of total direct N_2O emissions from managed soils.

Source: own elaboration

Figure 4. EU-28 emissions in the category 'agriculture' in 2017 (CO_2eq)



Note: CAPRI covers 98.4% of agriculture emissions (not covered: 3.F, 3.H, 3.I, 3.J, 3.D.1.5, 3.D.1.7; Table 1)

Source: Own elaboration based on EEA (2019)

Figure 5 shows the EU-28 emissions and removals related to 'LULUCF' as reported to the UNFCCC by the EU (EEA 2019). Following the implementation of LULUCF emissions and removals in EcAMPA 3, CAPRI now covers the most important sources in this category, except Harvested Wood Products (HWP) (cf. Table 2).

Table 2. LULUCF reporting items to the UNFCCC and emission sources calculated and reported in CAPRI

	UNFCCC Reporting Sector LULUCF (CRF Sector 4)	CAPRI Reporting and modelling	
Carbon dioxide	4.A Forest Land		
	A.1: Forest land remaining forest land	FORFOR	Forest land remaining forest land
	A.2: Land converted to forest land	CRPFOR	Cropland converted to forest land
		GRSFOR	Grassland converted to forest land
		WETFOR	Wetlands converted to forest land
		ARTFOR	Artificial area converted to forest land
		RESFOR	Residual land converted to forest land
	4.B Cropland		
	B.1: Cropland remaining cropland	CRPCRP	Cropland remaining cropland
	B.2: Land converted to cropland	FORCRP	Forest land converted to cropland
		GRSCRP	Grassland converted to cropland
		WETCRP	Wetlands converted to cropland
		ARTCRP	Artificial area converted to cropland
		RESCRP	Residual land converted to cropland
	4.C Grassland		
	C.1: Grassland remaining grassland	GRSGRS	Grassland remaining grassland
	C.2: Land converted to grassland	FORGRS	Forest land converted to grassland
		CRPGRS	Cropland converted to grassland
		WETGRS	Wetlands converted to grassland
		ARTGRS	Artificial area converted to grassland
		RESGRS	Residual land converted to grassland
	4.D Wetlands		
	D.1: Wetlands remaining wetlands	WETWET	Wetlands remaining wetlands
	D.2: Land converted to wetlands	FORWET	Forest land converted to wetlands
		GRSWET	Cropland converted to wetlands
		WETWET	Grassland converted to wetlands
		ARTWET	Artificial area converted to wetlands
		RESWET	Residual land converted to wetlands
	4.E Settlements *		
	E.1: Settlements remaining settlements	ARTART	Artificial area remaining artificial area
	E.2: Land converted to settlements	FORART	Forest land converted to artificial area
		CRPART	Cropland converted to artificial area
		GRSART	Grassland converted to artificial area
		WETART	Wetlands converted to artificial area
		RESART	Residual land converted to artificial area
	4.F Other Land **		
	F.1: Other land remaining other land	RESRES	Residual land remaining residual land
	F.2: Land converted to other land	FORRES	Forest land converted to residual land
		CRPRES	Cropland converted to residual land
		GRSRES	Grassland converted to residual land
		WETRES	Wetlands converted to residual land
		ARTRES	Artificial area converted to residual land
	4.G Harvested Wood Products ***		*Not covered in CAPRI*
	4.H Other LULUCF		*Not covered in CAPRI*

* Settlements: the CAPRI terminology 'artificial land' deviates from the UNFCCC classification but coincides with the term used in Eurostat;

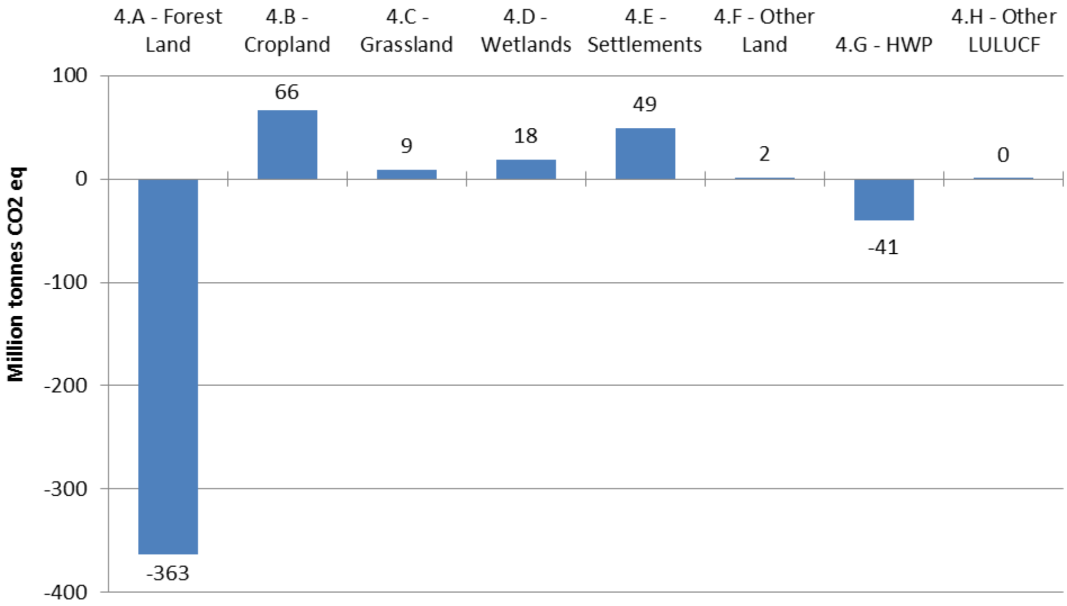
** Other land: the term was used in CAPRI already.

*** HWP: includes all wood material (including bark) that leaves harvest sites. Slash and other material left at harvest sites should be regarded as dead organic matter in the associated land use category and not as HWP.

Note: subcategories to cover GHG emissions from biomass burning (i.e. CO_2 and non-CO_2 gases) should be reported only for fires on managed lands and disaggregated by controlled burning and wildfires. For fires occurring on cropland and grassland, non-CO_2 emissions have to be reported under the agriculture sector, and only CO_2 emissions from woody biomass are considered under the LULUCF sector (Abad Viñas et al. 2015).

Source: own elaboration based on EEA (2019)

Figure 5. EU-28 emissions in the category 'LULUCF' in 2017 (CO_2eq)



Note: 4.G (Harvested Wood Products) and 4.H (Other LULUCF) are not covered in CAPRI (cf. Table 2)
Source: Own elaboration based on EEA (2019)

3 Technological GHG emission mitigation options covered in the analysis

In this section, we briefly describe the technologies and management options considered in EcAMPA 3, and summarise the major assumptions taken for their assessment in CAPRI. Most of the technological mitigation options discussed in here have been already implemented and described in EcAMPA 2. However, to render this report self-contained, we include the same basic description of the measures as in Pérez Domínguez et al. (2016) and include an update of the background literature. Additional information on the modelling approach is included in the description of anaerobic digestion and the measures targeting genetic improvements. Moreover, the assumptions for modelling precision farming, variable rate technology and low nitrogen feed were updated in EcAMPA 3. Furthermore, the measures 'increasing legume share on temporary grassland' and 'fallowing histosols' now also account for CO_2 emissions/sequestration, and 'winter cover crops' are newly incorporated as a technological mitigation option. In addition, as mitigation measures targeting ammonia emissions also have implications for non-CO_2 GHG emissions, some specific ammonia mitigation options have been included in EcAMPA 3. An overview of the technological GHG mitigation options covered in EcAMPA 3 is presented in Table 3.

Table 3. Technological GHG mitigation options included in EcAMPA 3

Mitigation option	Emissions targeted	New compared to EcAMPA 2
Crop sector		
1. Better timing of fertilisation	N_2O; (NH_3; NO_x; NO_3)	
2. Nitrification inhibitors		
3. Precision farming		Updated assumptions; farm size structure dependent cost functions for VRT
4. Variable rate technology		
5. Increasing legume share on temporary grassland	N_2O; CO_2	Inclusion of CO_2 sequestration
6. Rice measures	CH_4	
7. Fallowing histosols (abandoning the use of organic soils)	N_2O; CO_2	Inclusion of CO_2 emissions
8. Winter cover crops	CO_2	New mitigation option
Livestock sector		
9. Anaerobic digestion: farm scale	CH_4; N_2O	
10. Low nitrogen feed	N_2O; CH_4; (NH_3)	Updated assumptions
11. Feed additives: linseed	CH_4	
12. Feed additives: nitrate	CH_4	
13. Genetic improvements: increasing milk yields of dairy cows	CH_4	
14. Genetic improvements: increasing ruminant feed efficiency	CH_4	
15. Vaccination against methanogenic bacteria in the rumen	CH_4	

Note: Emissions in brackets are the emissions also affected in addition to the GHG emissions.

Mitigation measures targeting ammonia emissions also have implications for non-CO_2 emissions. Table 4 shows the specific ammonia mitigation options that are now also endogenously included in EcAMPA 3 in addition to low nitrogen feed (#10 above).

Table 4. Technological ammonia emission mitigation options included in EcAMPA 3 with implications on GHG emissions

Mitigation option		Emissions affected in addition to NH_3
Low emission housing		N_2O; CH_4
Air purification in animal housing		N_2O
Cover storage of manure	Two variants: low and high efficiency systems	N_2O; CH_4; NO_x
Low ammonia application	Two variants: low and high efficiency systems	N_2O; NO_x

Additional emission mitigation options assessed in this report are cow longevity and afforestation. However, these two options have not been implemented as mitigation options that can be endogenously adopted in the scenario runs. Instead, the effects of cow longevity have been tested in the form of a sensitivity analysis. Moreover, CAPRI is now also prepared to analyse the effects of an exogenously determined (e.g. policy induced) afforestation or conversion of cropland to grassland (cf. section 3.4).

As in previous EcAMPA versions, for the underlying assumptions on the mitigation potential, mitigation costs and adoption potential of the technological mitigation options we rely mainly on GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) data from 2013 (GAINS 2013; Höglund-Isaksson et al. 2012, 2013) and its updated version of 2015 (GAINS 2015; Höglund-Isaksson 2015; Winiwarter and Sajeev 2015; Höglund-Isaksson et al. 2016), as well as on information collected within the AnimalChange project (Mottet et al. 2015).

The technological mitigation options and underlying assumptions are briefly described in the following sections. The options related to the crop sector are presented in section 3.1, the ones related to livestock in 3.2. Section 3.3 presents the considered ammonia mitigation options and section 3.4 the additional mitigation options assessed. Finally, the CAPRI modelling approach for costs and uptake of mitigation technologies is outlined in section 3.5. Please note that the approach has not changed compared to EcAMPA 2, and we, therefore, use the same description as in Pérez Domínguez et al. (2016).

3.1 Crop sector related mitigation options

EcAMPA 3 covers eight crop sector related technological mitigation options, comprising the fertiliser related options (1) better timing of fertilisation, (2) nitrification inhibitors, (3) precision farming, and (4) variable rate technology, as well as (5) increasing legume share on temporary grassland, (6) rice measures, (7) fallowing histosols and (8) winter cover crops.

3.1.1 Better timing of fertilisation

Better timing of fertilisation means that the crop demand and the application of fertiliser and manure are more in line with each other (i.e. less asynchronous). A timely application of fertilisers, especially nitrogenous fertilisers, has several beneficial effects for the environment (Maciel de Oliveira 2018). When fertilisers are applied in the autumn but crops are planted only in the spring, considerable amounts of nitrogen can be lost and, therefore, transformed into GHGs before the crops can use it for plant growth. The magnitude of the fertiliser losses (some of which occur as N_2O emissions to the atmosphere) due to untimely fertiliser application depends on a number of field conditions, such as soil characteristics, weather variables and farm management factors (e.g. placement and form of fertiliser, rotation or tillage system). While appropriate timing of fertiliser application involves costs for the farmers (e.g. increased management costs as a result of more frequent soil analyses, and splitting of the application of fertilisers), it can also lead to higher yields and/or lower fertiliser requirements (Hoeft et al. 2000).

With respect to the underlying assumptions, the settings from GAINS (2013) are kept (i.e. the same as already used in previous EcAMPA studies), although GAINS has eliminated the measure from their actual database. Coefficients for better timing of fertiliser application have not been updated in GAINS, because the measure is economically dominated by Variable Rate Technology (VRT) according to the latest literature review (i.e. it achieves lower emission savings at higher costs). However, as we use different data for VRT in EcAMPA 3 (cf. section 3.1.4), this measure can still play a role.

The theoretical emission reduction potential of the mitigation option 'timing of fertilisation' is restricted by the regional over-fertilisation factors estimated in CAPRI.[9] More information on how this restriction works can be found in Annex 1, 'Restriction of fertiliser measures'.

3.1.2 Nitrification inhibitors

Nitrification is a natural biologically mediated process occurring in soils, converting ammonium to nitrite and then to nitrate (Li et al. 2018). Nitrification inhibitors (NI) can be applied to slow down the transformation of ammonium into other forms that result in nitrogen losses and have adverse effects on the environment. NI are chemical compounds that delay bacterial oxidation of the ammonium ion by depressing the metabolism of *Nitrosomonas* bacteria over a certain time period. These bacteria are responsible for the transformation of ammonium into nitrite (NO_2); a second group of bacteria (*Nitrobacter*) then converts nitrite to nitrate (NO_3). The objective of using NI is to control leaching of nitrate by keeping nitrogen in the form of ammonia for a longer time. This prevents denitrification of nitrate and reduces N_2O emissions caused by nitrification and denitrification (cf. Nelson and Huber 2001; Weiske 2006; Snyder et al. 2009; Akiyama et al. 2010; Delgado and Follett 2010; Snyder et al. 2014; Lam et al. 2015; Ruser and Schulz 2015).

NI could indeed be a powerful tool to decrease N_2O emissions, what is broadly supported by the existing literature (Rose et al. 2018). However, even though NI are applied and accepted in many countries such as the USA, there is still some discussion about their application in other world regions, due to possible negative health or environmental side effects, such as the appearance of traces in dairy products (e.g. the case of dicyandiamide being detected in New Zealand dairy products; OECD 2013). In addition, the effectiveness of NI depends on environmental factors such as temperature, soil moisture, etc., and the inhibitors sometimes seem to easily leach out of the rooting zone, which also lowers the effectiveness of the inhibitor (Akiyama et al. 2010, Rose et al. 2018).

As an upper limit for the application, we took the national share of urea (based on MITERRA), plus the percentage of nitrogen applied as ammonium (100 % of ammonium sulphates and phosphates, 50 % of ammonium nitrates and NPK fertilisers, i.e. fertilisers providing nitrogen, phosphorus and potassium). Besides this upper limit on the eligible area for NI, we followed the GAINS (2015) assumptions, assuming an N_2O emission reduction of 34 % for the use of NI, with costs of 86 Euro per tonne of nitrogen. In EcAMPA we assume that half of the effect (17%) is due to a general increase of nitrogen efficiency (i.e. reducing all nitrogen emissions simultaneously), while the other half comes from a reduction of the N_2O emission factor.[10]

([9]) Over-fertilisation is when the fertiliser is applied in excess of the actual crop need. Over-fertilisation factors are estimated in CAPRI on a regional basis (i.e. grouping all crop production systems in a NUTS 2 region).

([10]) This might not reflect correctly the relative changes of different emission types, since for instance N_2O and NO_3 decrease, but NH_3 increases.

In GAINS (2015), it is also assumed that NI can be applied to manure to the same extent and the same cost as to mineral fertiliser (i.e. a 34 % reduction of N_2O emissions can be achieved at a cost of 86 Euro per tonne of nitrogen applied). However, the literature and empirical evidence on the effectiveness of NI to reduce N_2O emissions related to manure application are rather scarce compared with mineral fertiliser applications. There seems to be good potential for the use of NI also in the context of manure application. However, the effectiveness depends on many factors, among others a thorough mixing of the fertiliser with the NI, along with the time and form of manure application to the field. Therefore, it is difficult to achieve estimates of potential emission reduction effects and other impacts related to the use of NI with manure application, which is why NI are not considered applicable for the reduction of emissions from applied manure so far and are only considered for mineral fertiliser application).

The theoretical emission reduction potential of the mitigation option 'nitrification inhibitors' is restricted by the regional over-fertilisation factors estimated in CAPRI (cf. footnote 9 and Annex 1).

3.1.3 Precision farming

Precision agricultural technologies (PATs) are a set of technologies aiming at the management of spatial and temporal variability. Optimal operation of PATs can potentially increase on-farm profitability, optimise yield and quality, reduce inputs and minimise environmental impacts. Under the constraint of limited land for agricultural production in the future, technologies of precision agriculture are regarded as a key pathway for commercial agriculture and support the sustainable intensification of agricultural systems (Balafoutis 2017; Barnes et al. 2019a,b). PATs can generally be applied to both crop and livestock production. However, in EcAMPA 3 we refer only to its application to crop production, considering it to be 'an information and technology-based crop management system to identify, analyse, and manage spatial and temporal variability within fields' (Heimlich, 2003). Thus, precision farming is a management concept that is based on observing, measuring and responding to inter- and intra-field variability in crops. Precision farming incorporates several technological tools, including variable rate technology (VRT), remote sensing technologies, Global Positioning Systems (GPS) and geographical information systems (GIS) that should all help to apply inputs and machinery more precisely. The goal of precision farming is optimising returns on inputs while preserving resources. As this managerial system enables the farmer to, among other things, make better use of fertilisers and fuel use, it also directly contributes to reducing GHG emissions (Auernhammer 2001; Du et al. 2008; Mulla 2013; Kloepfer et al. 2015).

In GAINS (2015) all the different technological tools that constitute precision farming (i.e. VRT, remote sensing technologies, GPS and GIS) are merged into one composite measure called 'precision farming'. Only VRT is separated, as it is considered to be a single precision farming technology of wider application and lower implementation costs (see 'Variable Rate Technology' below). Regarding the GHG emissions related to precision farming, only the reduction in N_2O emissions is taken into account in the CAPRI modelling system at this point. For the inclusion of precision farming as a mitigation technology option in EcAMPA 3 we follow the assumptions of the updated GAINS (2015) data and assumed a potential reduction of N_2O emissions of 36 % (cf. GAINS 2015; Winiwarter and Sajeev 2015).

The theoretical emission reduction potential of the mitigation option 'precision farming' is restricted by the regional over-fertilisation factors estimated in CAPRI (cf. footnote 9 and Annex 1).

3.1.4 Variable Rate Technology

VRT is a subset of precision farming. As mentioned above, the crop yield potential can vary considerably within a field and VRT is a method to control this variability on a field by allowing variable map- and sensor-based rates of fertiliser and chemical application, seeding and tillage within a field (Du et al. 2008; Lawes and Robertson 2011; Kloepfer et al. 2015). Thus, VRT enables changes in the application rate to match actual needs for fertiliser, lime, seeds, etc. in that precise location within the field. The basic idea is that, according to an electronic map or specific sensors, a control system calculates the input needs of a crop on a specific soil and transfers the information to a controller, which delivers the input to the location (Balafoutis 2017; Barnes et al. 2019a,b). In EcAMPA 3, with VRT we refer to a combination of sensor technologies and auto-steer that is used to apply a site-specific and variable application of fertiliser (i.e. the rate of fertiliser application is based on the needs of the precise location), which optimises the fertiliser application.

In previous EcAMPA studies, the assumptions on VRT from GAINS (2015) were not followed because these assumptions were solely based on studies related to US agriculture, where the average farm size is considerably larger than in the EU, and, therefore, may not be adequate to be applied to the EU. Instead, assumptions and data based on EU literature were provided by KTBL (2015) and used in EcAMPA 2. However, the assumptions taken by KTBL (2015) were quite different from the ones used in the GAINS model, with the consequence that the technology 'VRT' showed lower emission reduction efficiencies but higher costs than the technology 'precision farming', which is in contradiction to the original definition of 'VRT', being a subset of measures from 'precision farming' with lower implementation costs. In order to remove this inconsistency, in EcAMPA 3 we implemented VRT costs and mitigation effects provided by the Scotland's Rural College (SRUC) (cf. Eory et al. 2015). Although this has not yet lead to a really harmonised set of assumptions for precision farming and VRT, the new data on VRT at least guarantees that both costs and emission reductions are lower than the GAINS based technology precision farming.

In contrast to GAINS, where cost information is based on average values of different studies with different sets of technologies for VRT, SRUC provides explicit assumptions on the respective technologies, so that VRT could be specified as a combination of sensor technologies and auto-steer. This corresponds to the definition of VRT in GAINS. The current specification is, therefore, fully consistent and transparent in terms of the meaning of VRT and precision farming. Similar to GAINS, however, costs appear to be lower and mitigation effects for VRT higher than suggested by the estimates provided by KTBL (2015).

The assumptions used in EcAMPA 3 regarding cost and mitigation effects of VRT can be summarised in Table 5.

Table 5. VRT assumptions in EcAMPA 3

Investment costs	5000 GBP (sensor), 5000 GBP (auto-steer)
Amortisation period	15 years (sensor), 5 years (auto-steer)
Variable signal costs per year	250 GBP
Maintenance costs per year	500 GBP
Training costs per 5 years	500 GBP
Mineral fertilizer saving (N)	27.1%
Other cost savings	5.4 GBP per ha[11]
Default N application	140 kg/ha

Source: Eory et al. (2015)

Considering a GBP/EUR exchange rate of 1.3 and an interest rate of 3.5% we get the following values for yearly costs per farm for the two technologies covered by our VRT measure:

$$C_{VRT} = \left(5000 * \frac{1.035^{15} * 0.035}{1.035^{15} - 1} + 5500 * \frac{1.035^{5} * 0.035}{1.035^{5} - 1} + 250 + 500\right) * 1.3 = 3123\ \text{EUR}$$

(Note: The 5500 for auto-steer include investment and training costs which are both amortised after five years)

([11]) The original number is 13.5 GBP per ha, including cost savings from mineral fertiliser. Assuming 60% savings from mineral fertilizer leads to 5.4 GBP for other savings.

These costs need to be reduced by the respective cost savings, which are dependent on the farm size (i.e. they are generally related to the number of hectares planted or the amount of fertiliser input). Cost savings from fertiliser reduction are endogenous in CAPRI.

In EcAMPA 3 the use of farm structure information has been extended from anaerobic digestion plants to the fertiliser measure VRT. This allows to better consider the regional farm size structure and to estimate adoption rates according to regional characteristics.[12]

The former calibration of the mitigation cost curves for fertiliser measures under EcAMPA 2 was based on a single observation on net unit costs for one technology and region. In the standard calibration approach for mitigation measures we would relate the cost information to the mineral fertilizer applied on an average farm (i.e. 140 kg multiplied by the number of hectares planted), and then, based on a series of assumptions, derive a linear average cost function (cf. Pérez Domínguez et al. 2016). In this procedure we would use assumptions on subsidies (s_i) and the respective implementation shares of the technology in at least two situations, usually the implementation in the base year (m_0) and the maximum possible implementation (m_1). However, in analogy to the implementation of the mitigation option "anaerobic digestion", the slope of the mitigation cost curve could also be estimated based on information on farm size structure. This farm size approach was implemented in EcAMPA 3, which allows replacing some assumptions on the responsiveness by statistical information, assuming that there is no correlation between farm size and individual preferences for the adoption of measures.[13] In this approach, differences in the adoption are exclusively determined by accounting or direct costs, which again are estimated based on the farm size.

In order to derive farm size dependent cost curves, we took the information on the regional farm size distribution from the farm structure survey 2013, using the average area of arable land per farm for arable land size classes for each NUTS2 region. First, for each of the nine accumulated arable land size classes (accumulated in the sense of containing all farms in the class and all larger classes) we calculated the cost of the technology (VRT) per tonne of mineral fertiliser N applied, assuming 140 kg of N per ha and year. Second, we mapped these costs to the share of the accumulated arable land size classes in the total arable land (a number between zero and 1). Finally, we approximated the resulting non-linear cost curves by a linear function, giving higher weights to the larger farm size classes. Weights, on the one hand, are based on the share of arable land represented by a size class. On the other hand, higher weights are given to larger farms because we assume that farms below 80 ha are too small to adopt the technologies and, consequently, the error in the cost estimation is kept smaller if we give low priority to farms in small size classes.

The example in Table 6 demonstrates the procedure. Assume a region with 100 farms, 5000 ha of arable land and three farm size classes (<20ha, 20-100ha, >100h) with the following distribution:

Table 6. Farm size distribution in a fictive region

Farm size class	Number of farms	Arable land per farm	Total arable land
< 20 ha	50	10 ha	500 ha
20-100 ha	40	50 ha	2000 ha
> 100 ha	10	250 ha	2500 ha

This leads to the following distribution of accumulated land size classes and the respective average farm sizes. From the cost calculation presented above based on SRUC data, we can derive the following average costs (not considering fertiliser savings) per tonne of N applied for VRT (see last column in Table 7):

([12]) It should be noted that the GAINS model data has also been revised after its use within the EcAMPA 2 study. The current GAINS version has an extended consideration of farm size effects on adoption possibilities and costs as well.

([13]) This no-correlation assumption concerns other costs than accounting costs, e.g. transaction costs. These are sometimes referred to as 'unobserved' or 'calibration' costs.

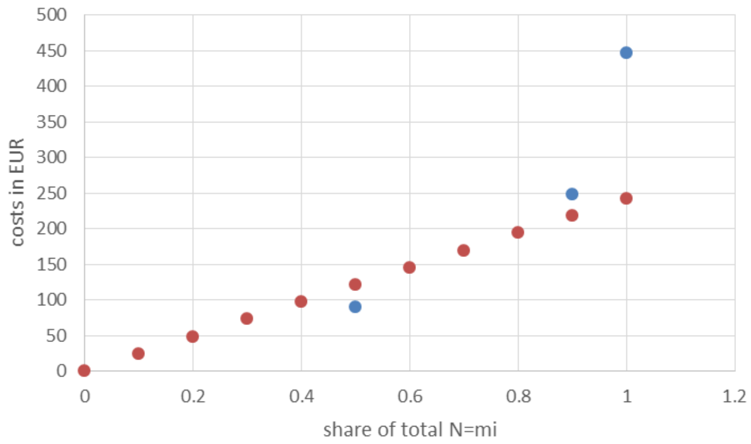
Average costs VRT (> 100 ha) = 3123 EUR / 250 ha / 140 kg/ha*1000 = 89.23 EUR/t

Table 7. Average costs per accumulated farm size class for VRT in the fictive region

Accumulated farm size class	Share of arable land	Average farm size	Average costs VRT
>0 ha	100%	50 ha	446.17 EUR
>20 ha	90%	90 ha	247.88 EUR
>100 ha	50%	250 ha	89.23 EUR

Assuming the same application rate of N for each ha (140 kg/ha), we can depict the share of arable land versus the cost observations (blue points in Figure 6), and run a weighted least square procedure for the linear approximation of the costs (orange points in Figure 6). Furthermore, we need the restriction of positive costs if cost savings are not considered.

Figure 6. Observed average costs (blue points) and linear approximation (red points) in the fictive region



3.1.5 New calibration of mitigation technology costs for fertiliser measures (mitigation options 3.1.1 to 3.1.4)

In the EcAMPA 2 study, the calibration of mitigation technology costs for fertiliser measures used cost information not entirely consistent with its original use in the GAINS model. In GAINS the fertiliser application is not changing in response to mitigation measures such as VRT or precision farming. Instead the associated emissions are reduced without specifying whether emission reductions come through savings in fertiliser application or through changes in the soil-plant system such that at a given fertiliser input there are nonetheless lower emissions. Costs are expressed in GAINS per tonne of N applied, which is not changing. In CAPRI these costs have been adapted and applied to the fertiliser use in a given scenario. For instance, fertiliser use is declining in a typical CAPRI mitigation scenario where higher adoption of VRT or PF is considered as the main channel to save fertiliser-related emissions. This involves an unplanned reduction in abatement costs: costs per ha are effectively reduced compared to GAINS according to the assumed savings in fertiliser application. This accounting error is corrected in the revised calibration.

In EcAMPA 2, the net cost function of N fertilisation for a given mitigation technology was:

$$C(mi) = (\alpha * mi - r * mi - si * \alpha * mi + \beta * mi + 0.5 * \gamma * mi^2 + p) * N(mi)$$

where mi is a number between zero and one, representing the share of the applied nitrogen for which the respective technology is in use. m_0 is the initial share, m_1 the share in case of maximum implementation (which is set to the share of farms larger than 80 ha in total arable land[14]). α is the reported (i.e. from GAINS) net cost of the technology (per unit of N

([14]) As can be seen from Figure 6, the cost function is quite non-linear in the final part where the smallest (high cost) farms would start adopting the technology. This part is avoided if we consider the technology not applied), β and γ two parameters controlling other driving forces behind the adoption of the measure (to be determined in the calibration). si is the share of the reported net cost α which is supposed to be received as subsidy, *p* is the fertiliser price and $N(mi)$is the amount of N fertiliser applied (depending on mi). *r* represents other cost savings per tonne of N applied (e.g. diesel).

This cost function gives lower cost than GAINS because GAINS reports the costs based on the N applied before the application of the measure, while the function above multiplies these costs with the N applied after the application of the technology. Therefore, in EcAMPA 3 the cost function of N fertilisation was changed to:

$$C(mi) = (\alpha - si * \alpha - r) * mi * N(m_0) + (\beta * mi + 0.5 * \gamma * mi^2) * N(m_0) + p * N(mi)$$

The key change to remove the inconsistency with GAINS is that terms related to α, (i.e. the reported cost of the technology from GAINS) is multiplied with $N(m_0)$, the initial N application, whereas it is to some extent arbitrary if the second bracket is multiplied with initial or final N application. Multiplying also the second bracket with $N(m_0)$ gives more transparent code and has, therefore, been selected.

Setting the first derivative of $C(mi)$ to zero for m_0 and m_1 and the respective s_0 and s_1 gives the following solution for β and γ:

$$\gamma = \{p * \delta * [(1 + \delta * m_1)^{-2} - (1 + \delta * m_0)^{-2}] + \alpha * (s_1 - s_0)\}/(m_1 - m_0)^{-1}$$

$$\beta = \alpha * (s_0 - 1) - \gamma * m_0 + r + p * \delta * (1 + \delta * m_0)^{-2}$$

with

$$\delta = \frac{N(m_0)}{N(m_1)} - 1$$

For technologies with farm-size dependent cost functions, γ is supposed to be determined by the linear approximation of the regional average cost function (the methodology is presented above in the section on VRT). For these technologies, we only have to determine β, in order to calibrate the cost function to m_0 with the subsidy rate s_0.

3.1.6 Increasing legume share on temporary grassland

The positive effects on GHG emissions of increasing the share of legumes on temporary grassland are twofold. First, it improves the soil carbon content and, second, it reduces the need for nitrogen fertiliser application through the capacity of legumes to fix nitrogen in the roots (Daryanto et al., 2018). Following the assumptions taken in the AnimalChange project (AnimalChange 2015), the share of legumes on temporary grassland in the base year[15] is kept constant over time for each MS, based on Helming et al. (2014). It is assumed that this share can be increased to a maximum of 20 %, which is equivalent to a nitrogen fixation rate of 15 %. The biological nitrogen fixation processes lead to a reduction in fertiliser use.

It is often argued that one of the main advantages of higher legume shares on grasslands is the stimulation of carbon sequestration (cf. Soussana et al. 2004; Lüscher et al. 2014; Kumar et al. 2018). As we include CO_2 emissions (and savings) in EcAMPA 3, we also reviewed the positive effects of increasing the legume share on sequestration. After some interaction with experts in the field we concluded that the increased carbon sequestration effect apparently comes via higher yields, while soil respiration is supposed to be unchanged. In order to avoid calibration issues, we decided to adopt a simplistic approach in CAPRI, ignoring any effects on grassland yields while still quantifying the effect on carbon sequestration. Lüscher et al. (2011) suggest an additional carbon sequestration of 300 - 500 kg C per ha and year when increasing substantially the legume share. We assume the average, i.e. 400 kg C. In CAPRI this mitigation measure aims at achieving a

suitable for the smallest farms such that the linear approximation only applies to larger farms and hence works well. The chosen threshold of 80 ha matches with a class limit in the Farm Structure data of Eurostat.

([15]) The base year refers to the last year(s) for which we have a full dataset to run the CAPRI model ex-post. For ECAMPA3 the year 2008 has been used.

legume share of 20%. Logically, the maximum increase will depend on the current (base year) regional legume share in temporary grasslands, which is exogenous. At the same time, we assume that the 400 kg C can be achieved if the region increases the legume share from the default value of 6.5% to 20%. If the initial share is higher, the potential increase of carbon sequestration is reduced proportionally.

3.1.7 Combined measures for rice cultivation

Globally, rice paddies are a major source of CH_4 emissions (Zaw Oo et al. 2018). However, the technological mitigation options targeting emissions from rice cultivation are of rather minor importance in the EU-28, since rice cultivation accounts for only 0.6 % of total GHG emissions in agriculture. Nonetheless, these options may help to reduce agricultural emissions in some EU regions. The current implementation is the same as in EcAMPA 2 and based on the updated literature review by the GAINS team (Höglund-Isaksson 2015). Compared with previous GAINS applications, the choice set has been simplified such that there is currently only one mitigation option that combines intermittent aeration, selecting specific rice varieties and sulphur application. Otherwise, the parameters and cost assumptions have been maintained in GAINS since 2013 and CAPRI has adopted these coefficients.

3.1.8 Fallowing histosols (abandoning the use of organic soils)

Histosols are soils consisting primarily of organic materials. 'Histosols' is the effective international standard name for organic soils. Other names include peat soils and muck soils, and histosols appear in national soil classifications under other names such as Moore (Germany) and organosols (Australia). The definition of what makes a soil a histosol is complex, referring to the thicknesses of soil layers, the organic content of these layers and their origin, underlying material, clay content and annual period of water saturation (Couwenberg 2011). Guidelines for the classification of organic (peat) soils are given in IPCC (2006).

Flooded peatlands are very efficient carbon sinks (Leifeld and Menichetti 2018; Wang et al. 2018), as water acts as a barrier for oxygen, creating conditions where mineralization of organic matter is suppressed (Smith et al. 2007). Therefore, these lands can accumulate large quantities of carbon over a long time period because its decomposition is suppressed by the absence of oxygen under flooded conditions. To use these organic soils (histosols) for crop production, they need to be drained. This drainage leads to aeration and subsequent decomposition of the peat, which results in a substantial release of CO_2 and N_2O emissions. Thus, restoration/fallowing of histosols is considered an effective GHG mitigation option (Smith et al. 2007; Joosten 2009; Couwenberg 2011; Roeder and Osterburg 2012; Reed et al. 2013; Paustian et al. 2016; Krimly et al. 2016; Leifeld and Menichetti 2018).

In the EcAMPA 2 study, only the effects on N_2O emissions had been taken into account, but for EcAMPA 3 also the effects on CO_2 emissions and carbon sequestration are considered. In CAPRI, the mitigation option of fallowing histosols is considered by setting aside a certain proportion of the agricultural area in each MS. The adoption of this mitigation option is constrained by the shares of cultivated organic soils in the region, i.e. at a level of 100 % implementation the additional idle land would equal the total histosols area in a region. This means that, for example, in Finland, a 100 % implementation rate of the mitigation option 'fallowing histosols' may result in idle land equal to 10 % of the UAA, whereas in Spain, this is perhaps 0.5 % of the UAA. The direct costs of this measure considered here are the opportunity cost of land use (i.e. concurrent uses). However, there are additional other direct costs (e.g. related to rewetting) and indirect costs (e.g. transaction costs linked to regional land regulation) faced by the farmers to achieve a 100 % implementation rate of this measure. For the technical implementation into CAPRI it was necessary to introduce a second set aside activity to distinguish the protection of former cropland from former grassland, because the GHG emission coefficients for CO_2 from organic soils used for arable cropland and grassland are vastly different. Moreover, in CAPRI N_2O and CO_2 emissions from fallowing histosols are technically treated differently to follow the UNFCCC classification and reporting. Whereas N_2O emissions are attributed to 'agriculture', CO_2 emissions from fallowing histosols belong to 'LULUCF'.

3.1.9 Winter cover crops

The additional planting of winter cover crops is generally assessed as having positive effects for the management of soil erosion, soil fertility, soil quality, water, and weeds, as well as for biodiversity and the mitigation of GHG emissions. Moreover, winter cover crops are seen as a promising option to sequester carbon in agricultural soils (Poeplau and Don 2015).

Winter cover crops were already included in CAPRI because they are one of the options to comply with the 'Ecological Focus Area' constraint of the CAP greening policy. To this respect, winter cover crops are modelled as an activity without an output and formally without the need of additional area (i.e. it is not in competition with other crops). The area for cover crops is limited to the area not covered by regular crops during the winter season. Therefore, for each crop, a share of winter and spring crops is defined (wherever data is available based on regional statistics), and winter cover crops are limited to the area of the respective spring versions. Costs are implemented in a simplistic way as 25% of machinery and other input costs of the CAPRI category 'other fodder on arable land' (OFAR), and 50% of seeding costs respectively. For the initial application rates of winter cover crops we use data from the Farm Structure Survey on Agricultural Production Methods (SAPM), a survey carried out in 2010 to collect data at farm level in view of agro-environmental measures. Within SAPM, the MS collected information from individual agricultural holdings, the data was transmitted to Eurostat and aggregated at NUTS2 regional level.

The following effects on emissions are considered in CAPRI:

1) Winter cover crops increase carbon sequestration (i.e. reduce carbon losses) via a higher carbon input and a lower soil respiration. The carbon effect is based on simulations with the CENTURY agroecosystem model (differentiated by NUTS2 regional level) [16], and calculated from the difference in the share of the land covered with winter cover crops between the simulation year and the base year. This difference is taken because winter cover crops are already present in the base year, while carbon sequestration is only achieved from an increased share of the area under winter cover assuming that the carbon balance in the base year is already in equilibrium. The total cumulative carbon increase is divided by 20, in order to spread the effect over a standardized number of years (consistent with the 2006 IPCC guidelines).
2) Winter cover crops help reducing soil erosion. The estimation of the effect is based on the RUSLE equation (cf. section 2.3.2). For more details on the factors used see Panagos et al. (2015).
3) Winter cover crops reduce nitrogen losses from superficial runoff of N. For the effect on runoff we use an emission reduction rate of 35%, while the effect on leaching is ignored so far[17].

([16]) The simulations with the CENTURY model were carried out by Emanuele Lugato from JRC.D3 in Ispra (for more details see Lugato et al. 2014).

([17]) Eory et al. (2015) propose a 45% reduction of total leaching on the field as consequence of cover crops. This directly translates to N2O emissions from leaching. The Miterra model uses 25%. The current calculation of emissions from leaching in CAPRI renders the implementation of respective effects difficult. On the one hand, N leached is calculated as a share of the N surplus, currently not available in the regional supply models without transferring the entire N chain there. On the other hand, reduced N from leaching in the current implementation would automatically lead to an increase in N2 emissions (denitrification) by the same amount. However, it can be assumed that at least a part of the N not leached would be available for plants and increase the N efficiency. This could only be translated to the model by a change of the over-fertilisation factor. So, probably the total effect can be reflected only by a parallel change of the runoff factor, the leaching fraction and N efficiency.

4) We assume winter cover crops generally being legumes (under the perspective of maximising mitigation) and being to 100% left on the fields (no harvest). Therefore, in consistency with the general assumption in CAPRI that legumes fix 75% of their N need, winter cover crops would provide the respective amount of N to the main (future) crops, entailing an equivalent decrease of N inputs, in particular mineral fertilizers. This, accordingly, leads to lower CO_2 emissions in the production of mineral fertilizers, whereas, by contrast, lower N_2O emissions from mineral fertilizer application are offset by higher N_2O emissions from crop residues. The N fixed is consistently derived from the carbon input, applying a C:N ratio of 24 (which is an ideal ratio for microbial needs but is rather modest with regard to N fixation). Using cover crops with lower C:N ratios is possible and would lead to an even higher fixation of N. Moreover, it should be kept in mind that the share of legumes in observed winter cover applications is currently far lower than 100% because other crops fit better farm level rotation requirements. Therefore, mineral fertiliser savings from winter cover crops with a typical composition would be therefore lower than the assumed in CAPRI (i.e. 100% share for legumes).

3.2 Livestock sector related mitigation options

Technological mitigation options related to the livestock sector are anaerobic digestion, low nitrogen feed, linseed as feed additive, nitrate as feed additive, increasing milk yields of dairy cows by genetic improvements, increasing ruminant feed efficiency by genetic improvements, and vaccination against methanogenic bacteria in the rumen (see options 9 to 15 in Table 3).

3.2.1 Anaerobic digestion: farm scale

Anaerobic digestion (AD) is the biochemical conversion of organic matter in the absence of molecular oxygen that involves microorganisms. When this process happens in a sealed tank (i.e. anaerobic digester), biogas is produced (i.e. a mixture of about 55-75 % CH_4, 25-45 % CO_2 and traces of other gases) and can be used to generate electricity, heat and/or vehicle fuel (Holm-Nielsen et al. 2009; FNR 2013; Korres and Nizami 2013). A by-product of the AD process is digestate, a nutrient-rich substance that is usually used as substitute of manufactured fertilizers (Möller and Müller 2012).

Many different raw materials are used as feedstock for AD, ranging from manure, harvest residues and dedicated energy crops from agriculture, to organic waste products from the food/feed industry and households. Manure actually has a rather low biogas yield potential, which is why crop material and organic waste are often used as co-substrate to increase the yield of the biogas and make the AD plant more economically viable (Holm-Nielsen et al. 2009; Weiland 2010; Seppälä et al. 2013; Kalamaras and Kotsopoulos 2014).

AD is considered to have several environmental benefits. Apart from being a sustainable source of renewable energy, AD is a technology that has proven to be especially effective for reducing GHG emissions from livestock manure, particularly because it can considerably reduce CH_4 emissions from stored manure. AD also reduces N_2O emissions from livestock slurries (Clemens et al. 2006; Massé et al. 2011; Petersen and Sommer 2011; Petersen et al. 2013).

For modelling AD, we follow the assumptions used in the AnimalChange project (AnimalChange 2015), assuming that only farms with more than 200 livestock units (LSU) can use AD as an economically viable technological option to mitigate emissions from manure. Therefore, the adoption of AD is assumed not to be profitable for farms with less than 200 LSU.

Community-based ADs are not taken into account in our analysis as they may lead to additional GHG emissions from the pre-digester storage phase (depending on how the manure is stored and for how long) and during manure transportation to the community AD. These additional emissions could outweigh the emission savings from the AD.

Information on LSU has been taken from the EU farm structure survey (Eurostat 2014).[18] In the pre-digester phase of the process, CH_4 losses of 25 % are assumed for liquid systems not including natural crust cover. Leaching losses during the digester phase are assumed to be 3 %. CH_4 yield, revenues and CO_2 savings from reduced burning of fossil fuels are calculated based on Mottet et al. 2015. In Table 8 all the assumptions considered in CAPRI for modelling AD are summarized.

Table 8. AD assumptions in EcAMPA 3

Pre-digester storage CO_2 loss rate	2 %
Pre-digester storage CH_4 loss rate	25 %
CH_4 conversion factor of the digester	85 %
CH_4 leakage in the digester (% of CH_4 produced)	3 %
CH_4 density	0.67 kg/m^3
Energy content of CH_4	55 MJ/kg
Energy conversion factor of CH_4	277.8 kWh/GJ
Efficiency of heat generation	40 %
Heat used in the AD plant (% of the heat produced)	9 %
Heat sold on the market	30 %
Efficiency of electricity generation	36 %
Electricity used in the AD plant (% of the electricity produced)	12 %
Emission intensity of heating	0.26 kg CO_2/kWh
Emission intensity of electricity	0.33 kg CO_2/kWh
Heat price	National values based on PRIMES estimates (provided by IIASA).
Electricity price	

It has to be noted that specific subsidies to stipulate large-scale biogas production (as for example provided in Germany) are not taken into account, and also the electricity or biogas prices are not assumed to be subsidised. The modelling approach accounts for the normal heat and electricity prices, based on national values as provided by IIASA (more precisely by price estimates done with the PRIMES model for 2030). Nonetheless, selling heat and electricity increases the revenue of the farmers. These energy prices are split into country-specific prices for heat and for electricity based on the GAINS database (where not available prices from SRUC were used as substitutes). Total energy production is calculated on the basis of manure output, and the part sold is multiplied with the respective prices.

Net costs of AD are calculated as gross costs minus revenues. The gross costs of implementing and running the AD plant are calculated on the basis of the amount of manure (m³), which is an endogenous variable in CAPRI, and the regional farm size structure. This means that AD costs follow a cost curve that depends on regional farm sizes, with farms having more LSU having relative lower costs per m³ manure. Detailed information on the functional form of the costs related to AD is given in Mottet et al. (2015). The equation providing AD average costs (per animal head and year) was obtained from the literature as reviewed in MacLeod et al. (2010)[19].

3.2.2 Low nitrogen feed

Low nitrogen feed (LNF) is a technological mitigation option that reduces the crude protein (CRPR) intake of animals with the aim of lowering ammonia (NH_3) emissions from livestock (cf. van Vuuren et al. 2015). Essentially, a lower nitrogen content in feed reduces nitrogen excretion by animals and, consequently, NH_3 emissions. However, there are positive cross-over effects with regard to N_2O and CH_4 emissions. There is a direct linear relationship

([18]) In the Eurostat survey, only the category 100–500 LSU is available. We therefore simply divided the category 100–500 LSU linearly. Thus, if there are, for example, 100 animals in the category 100–500 LSU, then one-quarter, or 25, are allocated to the group 100–200 LSU and three-quarters, or 75, are allocated to the group of 200–500 LSU. This is a simplification and probably not accurate because of the asymmetric distribution. This assumption should be revised in the future.

([19]) MacLeod et al. (2010) provide a review of AD plant costs from p.158 onwards.

between the input of dietary nitrogen and the nitrogen excretion via urine and faeces. On average, livestock excrete about two-thirds of the dietary nitrogen intake via urine and faeces, and only one-third is transformed into the protein of animal products. N_2O emissions depend on the amount of nitrogen excreted by animals. Thus, if a lower nitrogen content of the fodder reduces nitrogen excretion, this also positively affects the N_2O emissions from livestock (Kirchgessner et al. 1994; Weiske 2006; Luo et al. 2010). Regarding CH_4, it is not clear in which direction a reduction of the nitrogen content of the fodder would affect emissions. LNF might affect feed intake and digestibility rate, which in turn can affect the level of CH_4 emissions from enteric fermentation and from manure management.

Following the approach taken in the AnimalChange project (AnimalChange 2015), only the reduction of N_2O emissions is considered for LNF in our study. Under EcAMPA 2 it was assumed that the measure achieves a maximum reduction of 50% of CRPR over-supply. Furthermore, it is assumed (both under EcAMPA 2 as well as under EcAMPA 3) that the option can be applied to 100% of monogastrics, 100 % of the indoor time of dairy cows and 50 % of the indoor time of other ruminants. As N_2O emissions are directly related to nitrogen excretion, and the CAPRI model derives nitrogen excretion directly from CRPR intake and nitrogen retention, there are no other assumptions needed to quantify emission reductions from this measure in CAPRI (Mottet et al. 2015).

The fact that the over-supply is not reduced completely acknowledges the difference between field trials and the real farm sector, i.e. in the real farm sector some waste will be unavoidable. Regarding the technical assumptions, van Vuuren et al. (2015) discuss LNF in view of ammonia abatement mostly based on examples from the pigmeat and dairy sectors, where reductions of up to 30% of ammonia are observed in trials. Recent assumptions in GAINS imply a reduction potential for ammonia emissions of 20% for pigs and hens, 15% for dairy and 10% for poultry fattening. If a given share of the total nitrogen loss is lost as ammonia (van Vuuren et al. (2015) suggest 25% for dairy) then these ammonia savings would also signal the size of possible total improvements in N surplus which are somewhat lower than the assumptions taken in EcAMPA 2 for the typical case (i.e. 50% reduction of the surplus).

In terms of costs, the survey of van Vuuren et al. (2015) collects quite diverse information, which is mostly expressed in terms of Euro per kg NH_3 saving, with a mean value of about 2 Euro for pigs and 2.3 Euro for dairy cattle. However, depending on the prices of soya meal, other ingredients or amino acids, the indicated costs vary from negative to above 60 Euro/kg. Klimont and Winiwarter (2015) report from the same survey lower costs than the mean. Overall the recent literature suggests that the costs of LNF (as well as the abatement potential) had been exaggerated in CAPRI so far, where 5% of feed costs had been assumed for the typical case. This may be illustrated in Table 9 for the case of dairy cows and the Netherlands.

Table 9. LNF assumptions in EcAMPA 3 for the example of dairy cows in the Netherlands

Cost per kg NH_3 abated	2.3 €/kg
Crude protein per head	1076 kg/head
Nitrogen per head	179 kg/head (= CRPR/6)
Crude protein surplus	21%
Crude protein surplus	37 kg/head
NH_3 abatement (GAINS)	15%
NH_3 abatement	1.4 kg/head (= 25% of N)
Costs	3.23 €/head
Feed costs	1136 €/head
Abatement costs / feed costs	0.3%
Compare, costs (GAINS)	1.95 €/head

Combining the information on the crude protein surplus, as estimated in CAPRI, with the abatement assumptions of GAINS and the cost per kg NH3 abated, gives about 3 Euro/head. Instead, the cost information in GAINS (for a specific scenario) gives about

2 Euro/head, i.e. according to both estimates much less than 5%*1136 Euro/head = 57 Euro, which was the EcAMPA 2 specification.

It should be noted that endogenous responses (i.e. substitution of cereals for protein feed) reduce the effective cost in the CAPRI model, but the recent evidence suggests that the cost of the LNF measure should be corrected downwards in future CAPRI analysis. For EcAMPA 3 the settings selected are applied to the typical case of a 15% surplus reduction at a 1% increase of feed cost, so we apply a downward correction both for the abatement effect as well as for the costs.

3.2.3 Feed additives to reduce methane emissions from enteric fermentation: linseed

Supplementing animal diets with lipids (i.e. vegetable oils or animal fats) is used to increase the energy content of the diet and to enhance energy utilisation by lowering dry matter intake and improving digestion (Doreau et al. 2015). The combination of decreased dry matter intake and (potentially) maintained or increased (milk) production improves feed efficiency and results in decreased CH_4 emissions from cattle. One of the most efficient dietary lipids is linseed (Doreau et al. 2015; 2018). However, the effectiveness of feeding linseed for decreasing enteric CH_4 emissions depends on the feed mix. Furthermore, feeding too much linseed can have negative effects on the overall diet digestibility (Martin et al. 2008; Chung et al. 2011; Eugène et al. 2011; Grainger and Beauchermin 2011; Nguyen et al. 2012; Marette and Millet 2014; Van Middelaar et al. 2014).

In EcAMPA 3 we follow the assumptions taken in the AnimalChange project (AnimalChange 2015), assuming that the emission mitigation option of feeding linseed can be applied to 100 % of the EU dairy cattle herd, but to only 50 % of other cattle categories, as the intake has to be constant and can be better controlled for dairy cows. The feeding of linseed is limited to a maximum of 5% of total fat in dry matter intake. Accordingly, the feed intake of linseed depends on the fat content of the diet, which is calculated endogenously in CAPRI and varies between regions. It is assumed that, for each per cent of fat added, a 5% reduction of CH_4 emissions from enteric fermentation is achieved (Mottet et al. 2015).

3.2.4 Feed additives to reduce methane emissions from enteric fermentation: nitrate

Bacteria from the rumen are able to use nitrate as alternative electron acceptors for hydrogen, which reduces CH_4 production. Thus, using nitrate as a feed additive can reduce CH_4 emissions from enteric fermentation (Alvarez-Hess 2018; Duthie 2018). The CH_4 reduction potential seems to be quite high but requires a careful dosage to avoid negative health effects to the livestock (Cottle et al. 2011; Hristov et al. 2013; Bannink 2015).

Following the AnimalChange approach (AnimalChange 2015), we assume that nitrate feeding can be applied in the EU-28 to 100 % of dairy cows and to 50 % of fattening cattle and replacement heifers (i.e. for the time they spent in the stable). Furthermore, it is assumed that, for dairy cows, adding nitrate to the feed is limited to the time of lactation (about 10 months/year). The intake of nitrate is limited to a maximum of 1.5 % of total dry matter intake. For each per cent of nitrate added, CH_4 emissions from enteric fermentation are assumed to decline by 10 %, so that the maximum reduction is 15 %. Furthermore, as dietary nitrate increases the excretion of nitrogen, an equivalent reduction of crude protein intake of 0.42 % for 1.5 % nitrate is assumed (Mottet et al. 2015).

We assume that the two feed additives linseed and nitrate can be applied separately but also simultaneously.

3.2.5 Genetic improvements: increasing milk yields of dairy cows

As mitigation options for dairy cow emissions we initially considered both specific breeding for lower CH_4 emissions and breeding for higher milk yields. So far we only opted for the implementation of breeding for higher milk yields. A general genetic selection of individual animals with lower than average CH_4 emissions is already possible at present. However, to really have a lasting GHG mitigating effect requires that the host animal controls its microflora, that the trait is heritable and that the effect is persistent. Furthermore, a selection for low CH_4-producing animals might come at the cost of productivity and fertility (i.e. with adverse effects on total GHG emissions per kilogram of meat or milk). Accordingly, intermediate GHG reductions through genetic improvements, aimed directly at reducing CH_4 emissions per ruminant are very uncertain (Eckard et al. 2010; Cottle et al., 2011; Axelsson 2013; Clark 2013; Hristov et al. 2013; Berglund 2015; Løvendahl et al. 2018).

Increases in milk yields imply reductions of GHG emissions per kilogram of milk and, therefore, breeding for enhanced productivity with maintained animal health and fertility can be an effective solution to reduce CH_4 emissions per dairy cow (somewhat smaller for non-dairy cattle and sheep). In the EU, there is actually already a broad breeding goal in the dairy sector, which is included in the dairy market medium-term prospects (i.e. in the baseline projections). However, average milk yields are quite diverse across MS and actually significantly below average in some countries. Therefore, the option of genetic improvements with regard to increasing milk yields per cow was already included in EcAMPA 2.

In CAPRI, we assume that breeding achieves some improvements in milk yields of dairy cows in those countries below the EU-28 'top group', which is defined in the model as Denmark, Finland, Sweden and Portugal. We take the simple average of the milk yields of these four countries to define the 'top yield' (about 10 tonnes per head in 2030). Other regions are assumed to catch up with the top group according to:

yield_new = yield_old + p_ghgTechMYld * (yield_top – yield_old)

Note that setting p_ghgTechMYld as 1 would imply that yields should increase in any other region to the yields of the top group (i.e. 10 tonnes per cow).

This specification appears basically still reasonable. The principle of catching up of most EU countries to the yield level of a top group has also been used in Höglund-Isaksson (2015). The degree of catching up has been set quite cautiously to p_ghgTechMYld = 0.2. Thus, for example, if the option 'breeding for higher milk yields' was implemented at a rate of 100 %, the following increase in milk yield would be achieved in Romania:

5.84 tonnes = 4.8 tonnes + 0.2 * (10.0 tonnes – 4.8 tonnes),

where average milk yields increase from 4.8 tonnes in the reference scenario in 2030 (in 2010: 3.5 tonnes) to 5.84 tonnes per head. In other words, while in Romania milk yields are projected to increase in the reference scenario by 2030 compared with 2010 by 37 %, a full uptake of the option 'breeding for higher milk yields' would result in an increase of Romanian milk yields of 67 % by 2030 compared with 2010.

The assumed accounting costs are reduced from 20 % (EcAMPA 2) to 10% (EcAMPA 3) of the additional revenue for genetic improvements of dairy performance (i.e. the increase in milk yield multiplied by the milk price in the baseline), with a minimum of EUR 20 per cow.

The specification of linking the cost to the economic benefit favours an EU-wide application that was considered of interest and also realistic. Given that the absolute yield potential may differ across regions, a uniform cost assumption, perhaps with some gross domestic product (GDP) adjustment, would have resulted in vastly diverging adoption rates across regions from 0 to 100 %. However, this was not considered plausible as the administrators of any breeding programme will have to make sure that it is attractive to farmers.[20]

([20]) While a reasonable order of magnitude for the cost share might be identified easily (certainly somewhere in the range of 5%-30%) the exact specification has been developed after some explorations. Rather low costs (for example 5% of the additional revenue) render the program attractive but has often led to high growth of production and market disruptions in single MS that even slowed down convergence of the model or created problems of infeasibilities in scenario simulations. These disruptions are not shared within the whole EU because raw milk is not economically tradable across long distances. Therefore raw milk markets have to clear at the national level in CAPRI which renders raw milk markets quite sensitive to political measures.

It is important to note that a frequent finding of testing different parameter settings for this measure is that the decline in milk and dairy prices and in the EU dairy herd is often not sufficiently large to counteract the increase in emissions induced by higher milk yields.[21] The effectiveness of this measure, therefore, may be modest from the perspective of achieving emission reductions in EU agriculture.

3.2.6 Genetic improvements: increasing ruminant feed efficiency

A further mitigation option related to genetic improvements is increasing ruminant feed efficiency. An increasing number of studies show that feed conversion efficiency (FCE) is a heritable trait of ruminants (Løvendahl et al. 2018). As in EcAMPA 2, and in line with GAINS, we also assume in EcAMPA 3 that the main effect (at a 100 % implementation rate) is a 10 % reduction in energy need of non-dairy ruminants, as this should reflect breeding for lower CH_4 losses. In addition, we assume that crude protein need would also decline by 5 % for two reasons: (1) such a decrease in crude protein need may be practically unavoidable if efficiency gains in energy use from breeding also extend to protein, and (2) in test runs with the model we saw that an exclusive reduction of energy need by 10 % creates strong incentives for changes in the feed mix towards protein-rich feed, which appeared implausible and sometimes even infeasible, in particular in regions that strongly rely on grass.

The feed efficiency gains reduce feed intake, which automatically reduces CH_4 emissions in the case of cattle[22] (Tier 2 calculation). For sheep (Tier 1 in CAPRI), we included a special reduction factor that also reduced CH_4 from enteric fermentation by 10 % if the measure is fully implemented. This different technical treatment is necessary because the accounting is simplified for sheep in CAPRI, but the key effect (10 % saving) is the same, as CH_4 emissions are a loss of feed energy. The order of magnitude (10 %) is based on the literature review by the GAINS team (Höglund-Isaksson 2015). Eory et al (2015) give for the UK a possible saving of about 580 kt of CO_2, which would be about 7% of the UK emissions from enteric fermentation according to Bioscience Network Limited (2012). Basarab et al. (2013) report an improvement of the 'carbon footprint' by about 20% in a model calculation that includes more CO_2 effects than from enteric fermentation. The possibility to save emissions via increased feed efficiency is, therefore, backed up by the literature, but additional clarification (i.e. time period, reference situation, effects included) would still be needed.

With respect to costs, we have reduced assumptions on accounting costs as in the case of breeding for higher milk yields from 10 % (EcAMPA 2) to 5% (EcAMPA 3) of the estimated savings in feed costs, with a minimum of EUR 2 per animal (which is considered low when the animals are sheep or calves). The savings have been estimated as the percentage reduction in energy requirements multiplied by the value of feed use in the reference run. The current cost specification in CAPRI was meant to render the measure attractive while also ensuring a positive cost. Eory et al. (2015), for example, do not provide costs, but indicate that efficiency gains in the farming sector would imply negative costs, which actually triggers the question why such programmes are not yet in place. Bioscience Network Limited (2012) present costs for feed efficiency when testing about 2000 animals per year, which could amount to 0.5-1 million GBP per year. Nonetheless, these costs are still clearly smaller than the benefits for the whole farming sector as reported in Eory et al. (2015) of about 10.3 -27 million GBP per year). Based on this literature, the revision in favour of lower costs has some support, but further evidence to justify the revised CAPRI assumptions (i.e. 5% of feed cost savings) has not yet been identified.

([21]) Higher milk yields also mean higher emissions per head, even though emissions per litre of milk produced may be reduced.

([22]) As in EcAMPA 2, we assume that the breeding programme targeting feed efficiency focuses on cattle in the production chain for beef, but excludes dairy cows and also breeding heifers, as they are targeted by the other breeding programme, which aims to improve milk yields.

3.2.7 Vaccination against methanogenic bacteria in the rumen

This technological mitigation option refers to vaccines that specifically target the CH_4-producing methanogens in the rumen (Wedlock et al. 2013). These vaccines are still in the development phase. They could have significant potential in extensive ruminant systems and, for example, the development of a vaccine against cell-surface proteins, which are common to a broad range of methanogen species, may improve the efficacy of vaccination as a CH_4 mitigation option. However, study results on vaccination against methanogenic bacteria in the rumen are rather inconsistent and further testing is needed before this option can be considered indeed viable (Wright et al. 2004; McAllister and Newbold 2008; Eckard et al. 2010; Hook et al. 2010; Wedlock et al. 2010; 2013).

Vaccination against methanogenic bacteria in the rumen was already incorporated as a technological mitigation option in EcAMPA 2, and the modelling assumptions remained the same in EcAMPA 3. The assumptions follow GAINS (2015), which basically means that vaccination against methanogenic bacteria reduces enteric fermentation of dairy and non-dairy cattle, as well as sheep, by 5 %. Furthermore, in GAINS, a cost of EUR 10 per animal per year is assumed for this technology (Höglund-Isaksson 2015).

3.3 Ammonia related mitigation options

The largest atmospheric loss of reactive nitrogen from livestock production systems is ammonia (NH_3) (Ti et al. 2019). Mitigation measures targeting ammonia emissions also have implications for non-CO_2 emissions. Ammonia mitigation measures were introduced in CAPRI for the first time around 10 years ago. The implementation was based on the Miterra-Europe model (cf. Velthof et al. 2007) and data from the GAINS model (at that time called RAINS, cf. Klimont and Brink 2004).[23] However, the modelling of endogenous technologies was not feasible at the time in CAPRI and, therefore, the implementation shares of the technologies were treated as exogenous (cf. Pérez Domínguez et al. 2012, 2016; Van Doorslaer et al. 2015).

In ECAMPA 3, ammonia measures are treated symmetrically to GHG mitigation measures in the narrow sense. Since most of the measures do also have implications for GHG emissions, this is an improvement, as synergies and trade-offs between ammonia and GHG mitigation measures can be included in scenario analysis. The ammonia mitigation options all relate to manure management and manure application.[24] The following have been implemented:

— *Low emission housing.* This includes flushing systems and other measures of immediate transport of manure into storage. The measure includes covered storage, and, therefore, cannot be combined with the 'covered storage' option mentioned below.

— *Air purification.* Acid scrubber systems to treat the air ventilated from animal housing.

— *Covered storage.* Measures to reduce the exposure of stored manure to the air, distinguishing low and high efficiency variants. The *low efficiency systems* include floating foils or polystyrene, whereas the *high efficiency systems* use concrete and corrugated iron or polyester caps.

— *Low ammonia application.* These measures aim at a minimisation of the surface exposure of manure applied to the fields, by placing manure under soil cover or vegetation. As in the case of storage measures, low and a high efficiency variants are distinguished. The *low efficiency measure* includes slit injection, trailing shoes, slurry dilution, band spreading for liquid slurry and incorporation of solid manure by ploughing into the soil the day after application. The *high efficiency measure* involves the immediate incorporation by ploughing within four hours after application, deep and shallow injection of liquid manure and immediate incorporation by ploughing of solid manure.

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[23] For a detailed description see Leip et al. (2010).

[24] Reductions in ammonia emissions due to low nitrogen feeding have been discussed in section 3.2.2.

Information on costs and applicability of technologies is taken from Klimont and Winiwarter (2011), and the information on emission reduction efficiencies and initial implementation shares are taken from Miterra (former implementation in CAPRI), which is based on Klimont and Brink (2004).

Cost calculation for ammonia measures

In accordance with the original data from GAINS, costs are calculated per animal place. Investment cost (I) are divided into a constant (c^f) and a farm size dependent (c^v) component. *n* is the number of animal places at the farm.

$$I = c^f + c^v/n \quad (5)$$

For *manure storage measures* the calculation is slightly different since costs depend on the manure output:

$$I = c^f * st * MV + c^v/n \quad (6)$$

st is the storage time (as a share of the year), and *MV* is the manure production per animal place (in m^3), which is derived from nitrogen excretion (endogenous in CAPRI) in dependence of manure management systems (liquid or solid) and animal types. In a final step, investment costs are annualised over the technical lifetime of the equipment (generally 10 years, but 15 years for high efficiency storage facilities), applying an interest rate of 3.5%.

Yearly operating costs (*O*) per animal place are determined by two components. One component is simply a certain share of investment costs, the second component depends on estimated additional expenses for electricity, gas, labour, water and waste disposal. The coefficients *s*, *q* and *p* are from Klimont et al. (2011).

$$O = I * s + \sum_k q_k * p_k \quad (7)$$

Operating costs for *manure application technologies* are calculated in a different way. No explicit investment costs are considered, and all costs are related to the manure volume and the shares of the manure applied on arable land and grassland. For manure deposited by grazing animals the technology is not applicable.

$$O = MV * a * \left(c^g * g + c^a * (1 - g)\right) \quad (8)$$

a = share of manure applied

g = share of manure applied on grassland

c^g , c^a = cost coefficients for the technology with respect to the application to grassland and arable land.

Both I and O are calculated for liquid and solid manure systems and then the weighted average, taking into account the share of the respective systems in a region, used to get the costs.

The ammonia technologies with non-zero coefficients c^v in the investment cost function are farm size dependent, as can be seen in equations 5 and 6. Based on fixed investment costs and operating costs we calculated cumulative average costs per animal place for each NUTS2 region, farm size class and animal type. In contrast to fertiliser-related mitigation technologies, farm size classes were defined via livestock units (LSU). Based on the regional distribution of animals in LSU-farm size classes (data from the farm structure survey 2010) linear cumulative average cost curves c*(mi)* per region and animal type were derived by approximation (*mi* being the share of animals in the region applying the respective ammonia technology).

$$c(mi) = \alpha + 0.5 * \gamma * mi \quad (9)$$

Calibration for ammonia measures

Total mitigation costs are:

$$C(mi) = (\alpha + \beta + 0.5 * \gamma * mi - s_i * \alpha) * mi * A \qquad (10)$$

with *A* being the number of animals in the region. Since *A* is independent from *mi*, the first derivative reduces to:

$$C'(mi) = (\alpha + \beta + \gamma * mi - s_i * \alpha) * A \qquad (11)$$

For ammonia technologies with farm size dependent cost curves we miss only β, which can be determined from s_0 and m_0 setting $C'(m_0)$ to zero:

$$\beta = \alpha * (s_0 - 1) - \gamma * m_0 \qquad (12)$$

For technologies without a farm size dependent component (manure application technologies and manure management technologies for poultry, sheep and goats), additional assumptions on the responsiveness are required (s_1 and m_1) in order to determine γ.

$$\gamma = \frac{\alpha*(s_1 - s_0)}{m_1 - m_0} \qquad (13)$$

3.4 Additional technological emission mitigation options

Cow longevity and afforestation emission mitigation measures could not been implemented in EcAMPA 3 as endogenous GHG emission mitigation options. Instead, they were tested in CAPRI in the form of sensitivity analysis and exogenous policy shocks.

3.4.1 Cow longevity

There are a number of potential additional technological measures to be considered for inclusion in CAPRI. Many of those are discussed for example in Eory et al. (2015) and a few, such as improved cow longevity, have been further investigated (Grandl et al. 2018). Improved cow longevity would imply lower replacement rates, what leads to a higher supply of (female) calves being available for fattening. Efficiency may increase, and globally this efficiency gain might lead to savings in emissions, unless the drop in prices strongly stimulates demand and exports. However, for EU emissions the effect may be (and has been at the time of EcAMPA 1), that emissions are increasing if the 'released' calves are used to expand the herd of heifers for fattening. In EcAMPA 3 changes in the cow replacement rate can be exogenously specified such that this measure can be analysed in the form of a sensitivity analysis.

3.4.2 Conversion of agricultural land

Supporting afforestation may be a promising measure to target LULUCF carbon effects. Based on the carbon accounting established within EcAMPA 3, CAPRI may also cover afforestation or the conversion of cropland to grassland as emission mitigation options to improve the carbon balance. Afforestation (and conversion of cropland to grassland) may happen as soon as corresponding policy instruments have been put in place, as for example a specific policy that targets an increase in afforestation. To analyse the effects of such an exogenously determined (policy induced) conversion of land, additional net afforestation can be implemented in CAPRI as an exogenous shift in the land allocation system. For this purpose it is necessary to specify the change in the forest area and a matching setting for the agricultural "asymptote". As the conversion scenario implies (by definition of "conversion") that the absolute increase in forest land (FORE) is matched with an equal decline in agricultural land (UAAR), we obtain in terms of the relative changes:

$$+\Delta(UAAR) = -\Delta(FORE) \Rightarrow \frac{\Delta(UAAR)}{UAAR} = -\frac{\Delta(FORE)}{UAAR} = -\frac{\Delta(FORE)}{FORE} * \frac{FORE}{UAAR} \qquad (14)$$

Therefore, a +1% increase in forest area compared to the baseline involves two additional interrelated exogenous area shifts:

1) -x% decrease in potential agricultural area with x% computed to give the same absolute decline in potential agricultural land as the absolute increase in forest area
2) -x% decrease in agricultural area (same as for potential agricultural area)

Some limitations have to be mentioned for the representation of support for afforestation in GHG-related policy scenarios:

1) The endogenous responsiveness of forestry is "passive" only in the current land allocation system of CAPRI. This means that the forest area adjusts (as "other land" and "artificial area") to changes in agricultural land in order to maintain the total land balance (according to the specified "land adjustment elasticities"). However, this mechanism is no substitute for a land allocation system that would also respond to changes in forest land rents (while maintaining land rents of agriculture and other land uses constant). This will be subject of further research.
2) Even though forestry does not respond to forest profitability in CAPRI at the moment, the existing endogenous land balancing mechanism prevents that exogenous shocks are passed on without modification to the final results. This is similar to the case of dietary shocks, which cause the ultimate change in consumption patterns to be an overlay of any exogenous shocks and endogenous responses to price changes.

3.5 The CAPRI modelling approach for costs and uptake of mitigation technologies

When looking at the potential of technological mitigation options, it is important to consider farmers' behaviour regarding technology adoption. The examination of factors influencing the adoption of technologies and management practices has been a focus of agricultural economics research for a long time (e.g., Sunding and Zilberman 2001; Knowler and Bradshaw 2007; OECD 2012; Dessart et al. 2019). Griliches (1957) was one of the first economists to analyse the adoption and diffusion of technological innovation in agriculture from an economic perspective, and he found that profitability was the largest determinant for the adoption of hybrid maize. Although many other studies confirm that profitability and profit maximisation are (some of) the most important drivers for the adoption of a certain production technology, the vast majority of the literature also points to various other characteristics that determine whether or not a technology is adopted by farmers. These other factors comprise mainly issues like uncertainty and risk involved in changing a management practice, farm size, simplicity and flexibility of the technology, as well as age, education and experience of the farmer (cf. McGregor et al. 1996; Barr and Cary 2000; and the reviews in Marra et al. 2003; Knowler and Bradshaw 2007; Prokopy et al. 2008; OECD 2012; Pierpaoli et al. 2013; Sanchez et al. 2016; Wreford et al. 2017). Such non-economic factors are often neglected in studies indicating would-be win–win mitigation measures (i.e. measures that are supposed to reduce GHG emissions and save costs at the same time) in the agricultural sector (Moran et al. 2013). In CAPRI, we specifically try to consider the influence of non-economic factors in terms of technology uptake.

The CAPRI methodology of modelling costs and uptake of mitigation technologies is described in detail in Pérez Domínguez et al. (2016). *The modelling approach of mitigation technology uptake in EcAMPA 3 did not change, but for completeness and to render this report self-contained we include the description here again*, although the text is the same as in Pérez Domínguez et al. (2016).

General specification of cost functions in the CAPRI supply module

The general modelling approach for the specification of cost functions in the CAPRI model is also used for the specification of costs involved in the adoption of a mitigation technology. The CAPRI supply equations are non-linear because, inter alia, the cost function is non-linear. With this, CAPRI considers that there may be other costs, known to farmers but not included in the pure accounting cost statistics, which increase more than proportionally when production expands.[25] These other costs may be the result of bottlenecks of labour and machinery use, but potentially also to the existence of risk premiums (i.e. risk aversion behaviour by farmers) or rotation constraints. Owing to these non-linear costs, farmers will not suddenly switch from one commodity (e.g. barley) to another one (e.g. maize), even if net revenues of the second commodity happen to increase further. A sudden and large switch to the production of a more profitable commodity (e.g. maize instead of barley) would be the outcome of a linear programming model and depicts a problem known as 'over-specialisation'. As this cannot be captured by statistics, CAPRI uses non-linear costs to reflect a rather smooth responsiveness by farmers to incentives that actually favour the switch to the production of a different commodity. These non-linear costs are known in the literature as 'calibration costs' and are a well-established and commonly used modelling approach (Howitt 1995; Heckelei and Britz 2005; Heckelei et al. 2012).

Specific approach for abatement cost curves

For commodity production, the 'responsiveness' to economic and political incentives is expressed in terms of (price–supply) elasticities, which illustrate the percentage increase in production of a commodity if the output price for that commodity increases by 1 %. For technological mitigation measures, responsiveness cannot be captured with elasticities, because most rates of adoption of the mitigation technologies are zero in the base year[26] and, therefore, elasticities cannot be defined. Instead, the responsiveness to applying a certain mitigation technology is measured in terms of the increase in the implementation share of this technology if a certain subsidy is granted for mitigation. This is illustrated below with an example where we consider the choice of the mitigation (implementation) share for a single fixed activity, where a subsidy, *S* (which is zero in the observed situation), is paid for mitigation and there is potentially also secondary revenue, *R* (e.g. from energy produced in anaerobic digestion plants). Thus, the problem is to minimise net costs of adoption:

$$\min_{mshar} N(mshar_{a,m,e}) = C^m(mshar_{a,m,e}) - S_{a,m,e} \cdot mshar_{a,m,e} - R_{a,m,e} \cdot mshar_{a,m,e}$$

where

mshar	vector of mitigation (implementation) shares
a	set of production activities (e.g. dairy cows)
m	set of mitigation technologies (including 'no mitigation')
e	emission type (e.g. CH_4 from manure management)
N	net cost function, equal to cost net of the subsidy
C^m	mitigation cost per activity level for mitigation option *m*, which depends on mitigation (implementation) share $mshar_{a,m,e}$ for activity *a*, mitigation option *m* and targeting emission type *e*
S	subsidy for implementation of the mitigation option *mshar*.
R	secondary revenue from implementation of the mitigation option *mshar*.

The specification used splits the CAPRI mitigation cost function, *C(.)*, into (1) a part coming from the cost database (i.e. GAINS and other sources) and (2) other costs not accounted

(25) This applies to the production of a certain commodity (e.g. maize) in a specific NUTS 2 region (e.g. Andalucía).

(26) As mentioned above, this information comes from the GAINS database.

for in that database. The latter are costs directly related to the determinants of technology adoption going beyond pure profitability considerations and are generally unknown (see previous section on the (non-)adoption of technologies by farmers):

$$C^{m}(mshar_{a,m,e}) = \left(\kappa_{a,m,e} + \beta_{a,m,e}\right) mshar_{a,m,e} + 0.5\left(\lambda_{a,m,e} + \gamma_{a,m,e}\right)\left(mshar_{a,m,e}\right)^{2}$$

where

$\kappa_{a,m,e}$ cost per activity level for full implementation of a certain mitigation option as given in the cost database; emission type *e* from activity *a*, if a mitigation technology *m* is used

$\lambda_{a,m,e}$ parameter for non-constant accounting cost per activity level for full implementation of a certain mitigation option, *m*, for emission type *e* from activity *a* (typically 0)

$\beta_{a,m,e}$, $\gamma_{a,m,e}$ (additional) cost parameters not covered by the cost database.

C^m can be interpreted as the average mitigation cost function for each activity unit actually applying the technology (i.e. the costs for the technology per commodity to which we apply the measure). Generally, we would expect average costs to increase with higher mitigation shares, which means that first we assume that those farms adopt the measure for which adoption is less costly.

For the parameter specification, two cases have to be distinguished, depending on whether or not the mitigation technology is already applied in the base year.

Parameter specification when the mitigation technology is already adopted in the base year

To specify the cost parameters that are not depicted in the cost database (i.e. the ones relating to the above-outlined determinants for technology adoption), we use two conditions. The first condition is the first order condition for cost minimisation at the observed share of mitigation (assumed here to be >0; the case of an initial share of zero is discussed below):

$$\partial N(mshar^{0}_{a,m,e}) \big/ \partial mshar^{0}_{a,m,e} = \partial C^{m}(mshar^{0}_{a,m,e}) \big/ \partial mshar^{0}_{a,m,e} - S^{0}_{a,m,e} - R_{a,m,e} = 0$$

where

$mshar^{0}_{a,m,e}$ current mitigation share according to historic data (GAINS database), *m0* in Figure 7

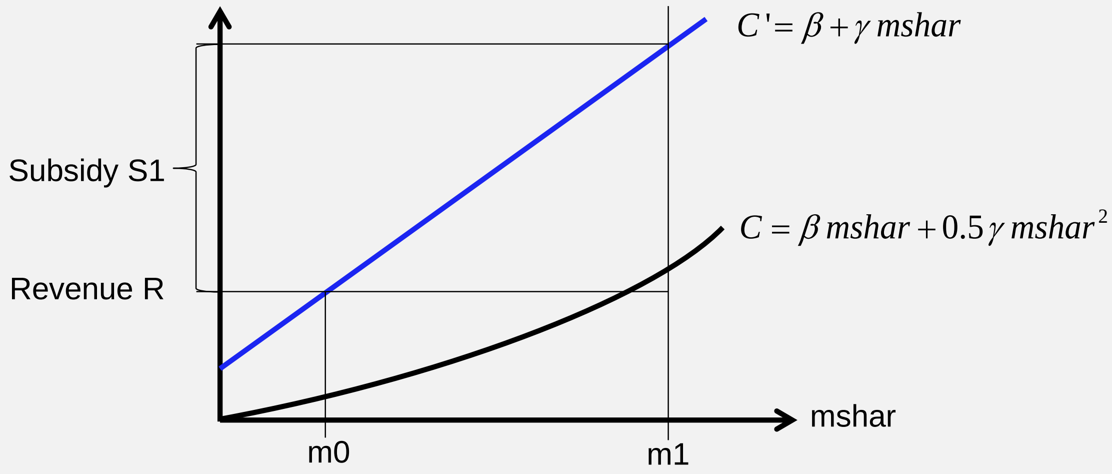
The second condition is an assumption related to responsiveness, namely the specification of a non-linear cost function with smooth behaviour of uptake of the technological mitigation options. For a certain subsidy, *S*, the optimal solution would be the implementation of a mitigation technology up to the technical limit (which is given in the GAINS database):

$mshar^{1}_{a,m,e} = mshar^{\max}_{a,m,e}$ (*m1* in Figure 7)

By definition then, the first order condition for minimisation of the net cost, *N*(.), should be zero at the maximum implementation share.

$$\frac{\partial N^{m}(mshar^{1}_{a,m,e})}{\partial mshar^{1}_{a,m,e}} = \kappa_{a,m,e} + \beta_{a,m,e} + \left(\lambda_{a,m,e} + \gamma_{a,m,e}\right) mshar^{1}_{a,m,e} - S^{1}_{a,m,e} - R_{a,m,e} = 0$$

Figure 7. Representation of mitigation cost curves in CAPRI with positive initial implementation

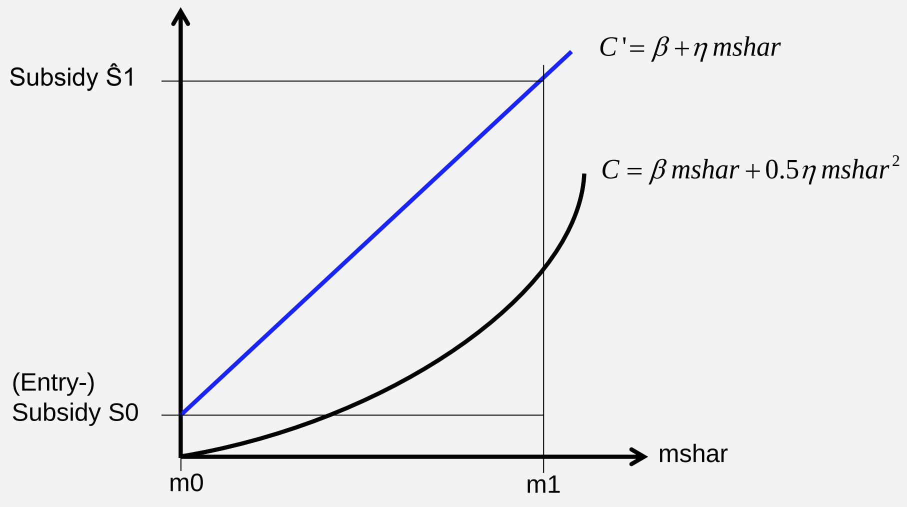


We assume for the time being that the implementation of a mitigation technology would be at its maximum if a relative subsidy ($S^1_{a,m,e}$) of 80 % of the accounting costs from GAINS ($\kappa_{a,m,e}$) is paid. The assumption of 80 % explicitly allows for some responsiveness of the farming sector to financial incentives for applying the technology. If a lower relative subsidy would be assumed (e.g. only 10 %), this would mean that farmers would quickly adopt the technology completely. However, this would be unrealistic, following the determinants of technology adoption outlined in the previous section. If a higher relative subsidy would be assumed (e.g. >100 %), this would mean that, for those farmers that are 'late followers' of adopting the technology, there would be near zero benefits of applying the technology.

Parameter specification when the mitigation technology is not adopted in the base year

There are several technological mitigation options that, according to the GAINS database, are currently not applied by the farmers (i.e. the uptake of these technologies is zero in the base year). This holds particularly true for newly developed (or to be developed) technologies. Zero implementation implies that it is currently not attractive for farmers to apply the technology. To model the cases with zero uptake in the base year, we assume that a relative subsidy ($S^0_{a,m,e}$) of 20 % of the accounting costs would be needed to make the technology attractive for the first adopter. Furthermore, as the technological mitigation options with an observed uptake of zero in the base year are apparently less attractive to farmers, full implementation by 'late followers' may be expected only at a higher subsidy rate. Our assumption for these cases is 120 % (rather than the assumed 80 % for those technologies already applied in the base year), which implies that the uptake of the mitigation technology by 'late followers' is more heavily constrained by (some of) the non-economic determinants for technology adoption outlined in the previous section. Thus, we assume that a higher incentive is needed to achieve full adoption of the mitigation technology by all farmers. This case is represented in Figure 8. A numerical example for a better understanding of this approach is given in Annex 1 of the EcAMPA 2 report (Pérez Domínguez et al. 2016).

Figure 8. Representation of mitigation cost curves in CAPRI with zero initial implementation



Sensitivity of our modelling approach for the uptake of mitigation technologies

It has to be stressed that the empirical evidence for the specification of the threshold values for the relative subsidies assumed in our modelling approach is difficult to come by or is non-existent, especially when considering the nature of future mitigation options. However, even if the presented approach may have a weak empirical basis, the alternative of using only the cost depicted in the GAINS database was considered further away from reality. For instance, this would imply that farmers are homogeneous in a region and would happily switch from one economic or production option to the next if the latter increases regional income by one Euro. Such 'jumpiness' in farmers' behaviour contradicts all anecdotal evidence and also the determinants for technology adoption outlined in the section on the (non-)adoption of technologies by farmers in the EcAMPA 2 report. Moreover, the use of step-wise adoption cost functions (i.e. typically used in technology-rich models) would make scenario analysis in an economic model such as CAPRI very difficult from a computational point of view. Annex 3 of the EcAMPA 2 report (Pérez Domínguez et al. 2016) provides a sensitivity analysis regarding the assumed relative subsidy necessary to achieve a 100 % adoption of a technology.

Source: EcAMPA 2 report (Pérez Domínguez et al. 2016).

4 Scenarios with selected technological mitigation options active

This chapter investigates the (theoretical) maximum mitigation potential of each technological option following the modelling approach and the assumptions taken in CAPRI and explained above. For the purpose of this analysis, the following scenario settings are applied:

- One scenario per technological mitigation option, i.e. only one mitigation technology is applied (active) at a time, whereas the uptake of the other technologies is 'frozen' to their baseline levels.
- In each scenario, the technology under investigation is assumed to be applied to the maximum extent possible.
- All scenarios are run *without market adjustments*, i.e. only the CAPRI supply model is active and hence there are no price feedbacks from global agri-food markets. Accordingly there are no trade effects calculated.
- Even without market adjustments, the forced adoption of the mitigation technology leads to adjustments in the optimal land use allocation and livestock production. These adjustments are due to the profit maximization framework of CAPRI.
- Each scenario (and hence technology) is compared to the baseline scenario 2030.

These scenario settings allow the analysis of the (theoretical) maximum mitigation potential and relevance of each technological mitigation option currently considered in CAPRI.

In previous EcAMPA reports the reference point of a 'full' implementation of technological GHG mitigation options was defined to give the maximum feasible implementation, even though this may still be only a fraction of the total basis for a certain mitigation measure. If, for example, 90% of farms in a country were too small to consider the installation of anaerobic digestion plants, then the 100% of the technically feasible mitigation may still mean only a 10% implementation in the whole country, which potentially could lead to misinterpretations of the results by the reader. This problem has been solved by adjusting the reporting to show the implementation as shares of the total activity levels that are at least partly eligible.

4.1 Scenarios with crop sector measures

In this section the following technological mitigation options are investigated: fertiliser measures such as optimised timing of fertilisation, precision farming, variable rate technology and nitrification inhibitors, as well as the measures increasing legume shares on temporary grassland, winter cover crops, fallowing histosols, and rice measures. Regarding the fertiliser measures it has to be noted that they may only be adopted if a certain rate of over-fertilisation exists (cf. section 3.1).

Table 10 shows (i) the mitigation directly achieved by the maximum application share of the specific technological mitigation option ('tech only'), and (ii) the overall effects on 'LULUCF' and 'agriculture' emissions in each scenario as a result of the CAPRI profit maximisation framework following the forced adoption of the mitigation technology (i.e. production effects considered, even in the absence of trade effects). The emissions are presented in CO_2 equivalents as absolute differences to the reference situation in 2030.

Accounting for emission reductions solely achieved by the application of a technological mitigation option ('tech only'), the largest benefits at aggregated EU level are realised by far with abandoning the agricultural use of histosols. The maximum application of fallowing histosols leads to the mitigation of 51.7 million tonnes (Mt) CO_2 equivalents, of which 81% (42.1 Mt) are 'LULUCF' emissions and 19% (9.6 Mt) are related to 'agriculture' (not shown in Table 10). The maximum application of winter cover crops reduces emissions by 17 Mt CO_2eq, which is entirely due to the mitigation of CO_2 emissions (-17.3 Mt) as N_2O emissions are slightly increasing (+0.3 Mt CO_2eq) (not shown in Table 10). The third measure for which CAPRI accounts the direct mitigation of both CO_2 and non-CO_2 GHG emissions is the increase of legume share on temporary grassland, which realises a direct emission reduction of 8.8 Mt CO_2eq, of which 92% (8.1 Mt) are 'LULUCF' and 8% (0.7 Mt) 'agriculture' emissions (not shown in Table 10). Taking only the direct N_2O emission reductions of the technology into account, precision farming achieves a mitigation of 12 Mt CO_2eq, nitrification inhibitors 11 Mt, and VRT 3.6 Mt, whereas the emissions reduction achieved by better timing of fertilisation is of rather minor magnitude. The application of the rice measures directly leads to a reduction in CH_4 emissions of about 0.7 Mt CO_2eq.

Accounting also for the adjustments in land use allocation and livestock production, the largest EU overall effects on 'agriculture' emissions are achieved by precision farming (-15.7 Mt CO_2eq), fallowing histosols (-12.6 Mt CO_2eq) and nitrification inhibitors (-12.3 Mt CO_2eq), which implies a reduction of 3.7%, 3% and 2.9%, respectively, of total EU agriculture emissions compared to the baseline. Noticeable reductions are also achieved with VRT (-4.2 Mt CO_2eq; -1%), winter cover crops (-1.9 Mt CO_2eq; -0.5%), increase of legume share on temporary grassland (-1.1 Mt CO_2eq; -0.3%) and rice measures (-0.8 Mt CO_2eq; -0.2%), whereas the better timing of fertilisation only reaches a reduction in 'agriculture' emissions of 0.1 Mt CO_2eq in the EU-28.

Accounting for the overall reductions of CO_2 emissions or carbon sequestration increases in the LULUCF sector, the largest benefits are obtained with fallowing histosols, which leads to CO_2 emission savings of 34.9 Mt, reflecting an increase in total EU LULUCF emission savings of 10.4% compared to the baseline. This is followed by emission savings due to the adoption of winter cover crops (20.2 Mt CO_2; 6%) and increasing the legume share on temporary grassland (8.8 Mt; 2.6%)

For each technological mitigation option the net effect on the aggregated LULUCF and agriculture emissions is a reduction in total emissions. In general, the positive mitigation effect ('tech only') on the 'targeted' emissions type is augmented once the land use allocation is adjusted to the application of the mitigation technology. This is especially the case with the fertiliser measures. The additional mitigation in 'agriculture' emissions is highest for precision farming, with an additional 3.7 Mt CO_2eq mitigated compared to the 'tech only' effect, followed by nitrification inhibitors (1.2 Mt CO_2eq) and VRT (0.5 Mt CO_2eq). For all these three measures, the additional mitigation comes mainly from an increase in set aside and fallow land as well as a decrease in total UAA (mostly at the expense of cereals area). The 'forced' adoption of mitigation options is bound to reduce profitability, since otherwise they would be adopted voluntarily, and this income loss is minimised by shifting away from the affected activities. However, it can also be seen that in some cases at MS and EU-28 level, the 'non-targeted' emissions type changes unfavourably (highlighted in red in Table 10), although these effects are dominated by the larger favourable effects in the targeted category. For example, all fertiliser-related mitigation options achieve a decrease in non-CO_2 emissions in the category 'agriculture' as these mitigation measures specifically target N_2O emissions related to mineral fertiliser application. At the same time, CO_2 emissions in the category LULUCF increase (i.e. carbon sequestration decreases) at EU-28 level due to soil carbon losses, more precisely due to CO_2 effects of agricultural soil management. This effect can also be observed in the rice measures scenario. Conversely, winter cover crops, fallowing histosols and an increase of legume share on temporary grassland have positive effects on both agriculture and LULUCF emissions. For fallowing histosols this leads to an accumulated EU GHG emissions decrease of 47.5 Mt CO_2eq and for winter cover crops of 22.1 Mt CO_2eq.

Table 10. Impact of each crop sector related mitigation measure implemented separately to the maximum share possible (one scenario per measure; LULUCF and agriculture emissions as absolute differences to the reference scenario 2030, 1000 t CO_2eq)

	Better timing of fertilization			Precision farming			Variable Rate Technology			Nitrification inhibitors		
	tech only	Overall effect		tech only	Overall effect		tech only	Overall effect		tech only	Overall effect	
		LULUCF	Agric		LULUCF	Agric		LULUCF	Agric		LULUCF	Agric
European Union	-81.3	6.6	-110.2	-12015.4	176.9	-15730.7	-3646.6	32.3	-4181.2	-11020.6	0.5	-12252.9
Austria				-72.4	-6.9	-59.8	-0.8	-0.1	-0.6	-85.3	-2.0	-83.1
Belgium	-4.4	0.1	-5.4	-286.6	-50.3	-394.7	-67.5	-0.5	-82.8	-178.2	-1.5	-204.3
Bulgaria				-363.6	-19.4	-461.1	-78.0	-1.1	-89.0	-382.9	-10.7	-429.2
Croatia				-93.8	-6.4	-127.5	-36.0	-0.4	-40.0	-86.9	-2.2	-100.0
Cyprus				-4.1	0.1	-7.2	-1.1	0.0	-1.3	-3.1	0.0	-3.8
Czech Republic	-7.8	1.3	-10.8	-456.1	-1.1	-678.5	-235.1	2.6	-286.5	-342.4	-3.7	-404.2
Denmark				-247.9	56.9	-306.4	-118.0	7.0	-139.5	-189.5	10.6	-211.4
Estonia				-66.1	-53.9	-98.4	-32.5	-5.1	-38.6	-51.6	-13.3	-61.3
Finland	-0.2	-0.0	-0.3	-163.1	-5.6	-229.8	-67.1	-0.3	-81.9	-131.3	-2.5	-148.8
France				-2007.9	-135.9	-2297.9	-749.9	-22.2	-821.7	-1784.8	-21.7	-1878.3
Germany				-1120.5	-106.1	-1310.4	-248.3	-2.5	-278.0	-1385.5	-79.3	-1456.2
Greece	-27.6	0.9	-31.8	-286.3	25.2	-351.0	-9.8	0.2	-10.8	-170.4	4.3	-182.9
Hungary				-163.2	3.2	-281.3				-291.8	-8.0	-324.9
Ireland				-486.7	65.7	-692.6	-96.6	2.4	-110.8	-392.3	16.1	-452.5
Italy	-4.4	0.7	-6.6	-569.3	6.7	-742.8	-137.1	2.2	-160.4	-599.7	9.7	-683.7
Latvia				-34.0	-17.6	-54.7				-54.0	-13.2	-70.0
Lithuania				-130.1	-35.0	-161.8	-10.7	-0.2	-12.2	-140.8	-16.9	-156.0
Malta	-0.2	-0.0	-0.2	-1.8	-0.4	-1.9				-0.9	-0.1	-1.0
Netherlands				-145.1	10.8	-121.9	-20.8	1.5	-11.0	-141.3	5.1	-122.3
Poland				-1796.4	247.0	-2609.1	-442.7	10.8	-514.1	-1635.8	70.8	-1918.4
Portugal	-0.1	0.0	-0.1	-100.2	65.1	-167.7	-30.7	3.4	-39.7	-87.0	22.9	-112.1
Romania	-1.4	0.6	-1.8	-594.4	-98.1	-743.3	-149.7	-9.6	-172.4	-554.4	-36.1	-608.5
Slovakia				-135.5	-2.5	-171.4	-47.2	0.1	-54.0	-132.5	-1.7	-149.1
Slovenia				-24.8	-12.9	-29.8	-3.7	0.0	-4.0	-24.7	-4.2	-26.9
Spain	-33.6	2.3	-51.1	-1386.2	128.6	-1966.2	-578.3	33.5	-672.1	-1048.2	34.6	-1189.9
Sweden	-1.8	0.9	-2.1	-210.4	29.4	-273.1	-96.8	2.4	-109.6	-160.1	5.8	-174.9
United Kingdom				-1069.2	90.3	-1390.4	-388.5	8.3	-450.4	-965.3	37.8	-1099.2

	Increase legume share on temp. grassland			Winter cover crops			Fallowing histosols			Rice measures		
	tech only	Overall effect		tech only	Overall effect		tech only	Overall effect		tech only	Overall effect	
		LULUCF	Agric		LULUCF	Agric		LULUCF	Agric		LULUCF	Agric
European Union	-8788.4	-8821.4	-1093.6	-16920.2	-20159.7	-1918.6	-51714.5	-34861.0	-12626.8	-651.8	127.9	-776.9
Austria	-179.5	-182.4	-15.3	-100.0	-115.3	9.4	-109.4	-74.8	-36.2			
Belgium	-91.5	-84.3	-13.4	-80.5	-116.1	-19.9	-0.2	-0.1	-0.2			
Bulgaria	-6.5	-7.4	0.1	-412.3	-435.4	-121.9	-737.7	-626.2	-98.1	-16.0	0.0	-16.1
Croatia	-81.8	-137.3	2.0	-216.5	-223.2	-8.9	-10.1	-9.4	-1.3			
Cyprus	-55.1	-53.4	-0.8	-0.0	0.1	-0.4						
Czech Republic	-3.4	-3.7	-0.0	-499.1	-523.3	-74.3	-73.8	-50.0	-25.1			
Denmark	-38.3	-36.2	-6.3	-192.9	-215.5	-20.9	-66.3	-52.8	-11.9			
Estonia	0.0	0.0	0.0	-150.6	-190.9	-11.5	-428.6	-310.2	-126.0			
Finland	-840.4	-783.0	-100.2	-703.6	-1279.1	-88.5	-19188.3	-11069.7	-3507.6			
France	-2052.2	-2051.5	-245.7	-2356.9	-2463.2	-122.6	-5100.1	-3871.2	-1271.0	-17.1	-0.0	-18.1
Germany	-445.2	-446.8	-48.0	-1883.8	-2764.8	-422.5	-7970.1	-5392.7	-3299.9			
Greece	0.0	0.0	0.0	-233.9	-246.4	-7.2	-881.6	-764.5	-121.1	-23.1	-0.1	-23.5
Hungary	0.0	0.0	0.0	-1178.9	-1294.8	-96.7	-3055.8	-2529.0	-373.0	-1.5	130.7	-98.7
Ireland	-596.3	-601.6	-51.2	-255.5	-256.0	-15.5	-58.7	-32.5	-45.7			
Italy	0.0	0.0	0.0	-1380.2	-1565.3	-109.0	-1148.0	-996.7	-146.4	-435.5	-2.9	-456.6
Latvia	-265.1	-369.3	-39.2	-178.4	-291.5	-20.7	-48.5	-35.6	-11.5			
Lithuania	-161.2	-152.5	-18.6	-384.3	-536.3	-59.1	-146.9	-85.9	-41.3			
Malta	-8.5	-8.3	-0.4	0.0	-0.3	-0.0						
Netherlands	-196.6	-166.1	-8.6	-132.5	-147.3	24.2	-3487.4	-2068.3	-1087.9			
Poland	-209.9	-222.6	-37.8	-1770.8	-2145.0	-259.2	-6363.4	-4724.8	-1681.7			
Portugal	-604.7	-549.5	-132.1	-149.6	-133.5	5.0	-5.6	-4.1	-2.1	-38.2	0.1	-38.9
Romania	-170.3	-180.9	-5.9	-1458.7	-1903.2	-278.1	-197.8	-157.9	-33.0	-12.5	0.0	-12.6
Slovakia	-3.7	-4.0	-0.1	-375.7	-403.6	-36.7	-6.0	-4.4	-1.4			
Slovenia	-32.0	-32.1	-1.6	-18.3	-20.6	-1.2	-273.1	-240.6	-61.0			
Spain	-616.5	-645.3	-104.0	-1413.7	-1503.9	-57.0	-852.9	-744.4	-115.2	-107.9	0.1	-112.4
Sweden	-596.3	-528.5	-66.6	-343.2	-367.5	-40.4	-1.9	-1.5	-0.6			
United Kingdom	-1533.6	-1574.6	-199.9	-1050.5	-1017.8	-84.9	-1502.3	-1013.6	-527.7			

Tech only = the mitigation directly achieved by the specific technological mitigation option. LULUCF and Agriculture = overall mitigation in the respective CRF sectors for each (maximum share) scenario.

The results presented in Table 10 have to be analysed within the context of the CAPRI assumptions. Table 11 presents the simulated implementation shares of each technology along with their feasible upper bounds for implementation at the country level. Upper bounds are not at 100% for the following measures:

— fertiliser measures, apart from nitrification inhibitors, due to the over-fertilisation constraint (cf. Annex 1);

— nitrification inhibitors, due to the country specific shares of nitrate and urea fertilisers;

— winter cover crops, due to the reference run results on crop areas compatible with winter cover crops (i.e. total UAA minus winter cover provided by regular crops).

Table 11. Implementation shares and upper bounds of implementation shares of mitigation measures related to the crop sector (one scenario for each measure)

	Better timing of fertilization		Precision farming		Variable Rate Technology		Nitrification inhibitors		Increase legume share on temp. grassland		Winter cover crops		Fallowing histosols		Rice measures	
	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound
European Union	4%	4%	53%	53%	28%	28%	60%	60%	100%	100%	31%	31%	100%	100%	100%	100%
Austria			28%	28%	1%	1%	54%	54%	100%	100%	22%	22%	100%	100%		
Belgium	11%	11%	83%	83%	30%	30%	54%	54%	100%	100%	38%	38%	100%	100%		
Bulgaria			38%	38%	14%	14%	56%	56%	100%	100%	34%	34%	100%	100%	100%	100%
Croatia			50%	50%	32%	32%	56%	56%	100%	100%	40%	40%	100%	100%		
Cyprus			83%	83%	27%	27%	57%	57%	100%	100%	33%	33%				
Czech Republic	11%	11%	67%	67%	56%	56%	54%	54%	100%	100%	27%	27%	100%	100%		
Denmark			63%	63%	51%	51%	54%	54%	100%	100%	40%	40%	100%	100%		
Estonia			63%	63%	51%	51%	54%	54%	100%	100%	36%	36%	100%	100%		
Finland	1%	1%	60%	60%	41%	41%	54%	54%	100%	100%	54%	54%	100%	100%		
France			50%	50%	34%	34%	57%	57%	100%	100%	25%	25%	100%	100%	100%	100%
Germany			32%	32%	14%	14%	61%	61%	100%	100%	29%	29%	100%	100%		
Greece	78%	78%	93%	93%	4%	4%	54%	54%	100%	100%	31%	31%	100%	100%	100%	100%
Hungary			18%	18%			59%	59%	100%	100%	47%	47%	100%	100%	100%	100%
Ireland			66%	66%	21%	21%	60%	60%	100%	100%	8%	8%	100%	100%		
Italy	4%	4%	59%	59%	23%	23%	76%	76%	100%	100%	35%	35%	100%	100%	100%	100%
Latvia			25%	25%			68%	68%	100%	100%	25%	25%	100%	100%		
Lithuania			32%	32%	5%	5%	54%	54%	100%	100%	33%	33%	100%	100%		
Malta	100%	100%	100%	100%			54%	54%	100%	100%	27%	27%				
Netherlands			39%	39%	10%	10%	54%	54%	100%	100%	42%	42%	100%	100%		
Poland			66%	66%	26%	26%	70%	70%	100%	100%	41%	41%	100%	100%		
Portugal			57%	57%	30%	30%	59%	59%	100%	100%	33%	33%	100%	100%	100%	100%
Romania	1%	1%	43%	43%	19%	19%	56%	56%	100%	100%	35%	35%	100%	100%	100%	100%
Slovakia			48%	48%	29%	29%	58%	58%	100%	100%	35%	35%	100%	100%		
Slovenia			49%	49%	12%	12%	60%	60%	100%	100%	21%	21%	100%	100%		
Spain	18%	18%	82%	82%	53%	53%	65%	65%	100%	100%	38%	38%	100%	100%	100%	100%
Sweden	5%	5%	65%	65%	50%	50%	54%	54%	100%	100%	32%	32%	100%	100%		
United Kingdom			53%	53%	33%	33%	57%	57%	100%	100%	12%	12%	100%	100%		

The EU average shown in Table 11 is computed as the average share among those regions where some implementation is technically feasible. Therefore, regions with zero upper bounds for optimised fertiliser timing are excluded from the average, just like regions without any histosols are excluded from the average implementation share for histosols protection and regions without rice production are ignored in the average for rice related measures. Table 11 shows that all measures are implemented to their upper bounds - as it should be according to the scenario definition.

Regarding the upper bounds of the fertiliser measures, it has to be recalled from Chapter 3 that these measures are realised according to the degree of over-fertilisation. In fact, for the measure 'better timing of fertilisation', upper bounds larger than zero only exist in 10 EU-28 countries, where the over-fertilisation rate is rather high. These bounds prevent that the cheap measures are selected if the over-fertilisation rate is projected to be low (i.e. when fertilisation is already better steered to plant needs), because in these cases it can be assumed that the cheap measures are already in place. In general, the over-fertilisation factors in CAPRI constrain the mitigation potential in a way that (i) the cheapest measures are implemented first, (ii) N input cannot be reduced below plant need, and (iii) the maximum reduction can be achieved by precision farming (cf. Annex 1). This constrains the maximum implementation of the measures 'better timing of fertilisation' and VRT, and contributes to their GHG saving effects to be only moderate even if they are implemented to their maximum possible shares. Moreover, the cost functions of VRT are derived from farm structure information and the technology is assumed to be only feasible on farms with more than 80 ha of arable land, which constrains the upper bounds of VRT application in addition to the over-fertilisation constraint.

Regarding 'increasing legume share on temporary grassland' it has to be reminded that, following the assumptions taken in CAPRI, the maximum application is reached with a legume share of 20% (cf. section 3.1.6). The implementation share of 100% indicated in Table 11 also includes the MS where the proportion of legumes on temporary grassland is already above 20% in the baseline, namely Greece, Hungary, Italy and Estonia. Accordingly, these four countries do not achieve any additional mitigation effects in the respective scenario (cf. Table 10).

4.2 Scenarios with livestock sector measures

In this section, we present results for the measures anaerobic digestion, low nitrogen feed, linseed and nitrate feed additives, genetic improvement measures that target an increase in milk yields of dairy cows and an increase in ruminant feed efficiency, respectively, and vaccination against methanogenic bacteria in the rumen. As in the previous section on crop measures, the reference situation in this section includes all technological mitigation measures 'frozen' to their reference run levels. In each measure-specific scenario, only the measure under investigation is not fixed and it is assumed to be applied to the maximum extent possible following the CAPRI assumptions and modelling approach taken (cf. Chapter 3).

Table 12 presents (i) the mitigation directly achieved by the maximum application share of the specific technological mitigation option ('tech only'), as well as (ii) the overall effects on LULUCF and agriculture emissions in each scenario as a result of the CAPRI profit maximisation framework. Emissions are shown in CO_2 equivalents as absolute difference to the reference situation in 2030.

The reduction in emissions achieved solely with the maximum application of the technological mitigation option ('tech only') is largest with anaerobic digestion (-12.7 Mt CO_2eq) and linseed as feed additive (-10.6 Mt CO_2eq). The maximum application of the options nitrate as feed additive and vaccination against methanogenic bacteria in the rumen directly reduce emissions by 7.8 and 7.7 Mt CO_2eq, respectively, whereas the measure low nitrogen feed results in a mitigation of 1.2 Mt CO_2eq. For the breeding measures 'milk yields' and 'ruminant feed efficiency', CAPRI is currently not able to report the 'tech only' mitigation effects, i.e. the emission reduction effects of the breeding programmes cannot be disentangled from their related effects on production levels and the production mix.

Taking also into account the adjustments in the optimal land use allocation and livestock production that follow the implementation of each measure, the mitigation effect is generally amplified with respect to agriculture emissions. At EU-28 level this is especially the case for the measure linseed as feed additive, for which the mitigation of agriculture emissions almost doubles after the adjustments compared to the mitigation achieved directly with the measure. The mitigation of 20.1 Mt CO_2eq implies a 4.7% reduction of total EU agriculture emissions compared to the baseline (Table 12). This is followed by anaerobic digestion (-10.5 Mt CO_2eq; -2.5%), nitrate as feed additive (-9.5 Mt CO_2eq; -2.2%), breeding for ruminant feed efficiency (-8.8 Mt CO_2eq; -2.1%) and vaccination (-8.7 Mt CO_2eq; -2.1%). So where do these amplified emission reductions compared to 'tech only' come from? As in the case of the hypothetical forced implementation of crop sector measures, we observe a decrease in animal (especially cattle) numbers and fodder activities, as profitability of targeted animal activities and related fodder production declines. In the case of linseed as feed additive, for example, the area for intensive grass and grazing decreases (-1.63 mio ha), and although extensive grass and grazing increases (by almost 0.5 mio ha), the net effect is a decrease in pasture area of 1.1 mio ha. While arable land increases (0.6 mio ha) also fallow and set aside area increase and the total UAA decreases by 0.3%, i.e. more than 0.5 mio ha. All these adjustments lead to a considerable augmentation of the 'tech only' effect.

In contrast to the other measures, breeding for milk yield increase in dairy cows leads to a rise in agriculture emissions of 1.9 Mt CO_2eq (+0.5%) compared to the baseline. This increase is not surprising, as the scenario forces a maximum adoption of the genetic improvement measure, and an increase in milk yields means an increase in emissions per cow (because a cow that produces more milk needs to eat more and hence also emits more). Without market feedbacks (e.g. decrease in milk prices) this inevitably leads to an increase in total emissions. Thus, breeding for higher milk yields is a special case, as GHG emission savings can only be achieved if market effects are sufficiently strong. This means that emission savings will only occur if a resulting decline in milk producer prices (as an effect of the increase in production) leads to a reduction in the dairy and heifers herd that at least compensates for the rise in emissions from increasing the yields per cow. This could only happen in the case of a very inelastic demand for dairy products combined with low trade responsiveness (i.e. no increase in the EU net trade position for dairy products).

The livestock sector-related mitigation measures target the non-CO_2 emissions of agriculture, but the measures can have adverse effects on the 'non-targeted' emissions in the LULUCF category (highlighted in red in Table 12). Such unintended effects can be seen in all scenarios (except the special case of breeding for higher milk yields) and are especially relevant in the cases of breeding for increased ruminant feed efficiency and the feed additive linseed, where aggregated EU-28 LULUCF-related CO_2 emissions of 4 Mt CO_2eq (1.2%) and 3.2 Mt CO_2eq (1%), respectively, are released compared to the baseline. In all cases, the increase in LULUCF emissions (decrease in carbon sequestration) is directly related to CO_2 emissions from soil carbon losses. About half of these are due to decreases in grassland area and increases in cropland, which in turn are direct effects of a declining need for fodder activities due to the technological mitigation measures targeting livestock feeding. The other main contribution to soil carbon losses comes from reduced carbon input due to somewhat reduced animal production and hence excretions.

Table 12. Impact of each livestock sector related mitigation measure implemented separately to the maximum share possible (one scenario per measure; LULUCF and agriculture emissions as absolute differences to the reference scenario 2030, 1000 t CO_2eq)

	Anaerobic digestion			Low nitrogen feed			Feed additive: linseed			Feed additive: nitrate		
	tech only	Overall effect		tech only	Overall effect		tech only	Overall effect		tech only	Overall effect	
		LULUCF	Agric		LULUCF	Agric		LULUCF	Agric		LULUCF	Agric
European Union	-12685.7	4.7	-10468.8	-1213.5	295.1	-1488.3	-10606.5	3210.9	-20100.7	-7769.2	573.2	-9510.0
Austria	-106.8	-0.7	-106.2	-11.9	6.3	-10.7	-267.2	145.7	-424.4	-203.6	79.3	-224.6
Belgium	-545.3	-1.4	-524.9	-20.5	2.0	-25.8	-262.1	20.5	-438.6	-172.6	-7.2	-165.4
Bulgaria	-12.2	0.0	-10.8	-8.4	1.7	-8.3	-80.2	17.7	-147.9	-48.1	-0.5	-57.8
Croatia	-11.5	0.4	-12.2	-3.9	0.4	-4.0	-46.6	6.7	-90.1	-31.2	-9.9	-23.4
Cyprus	-30.8	0.0	-30.2	-2.4	0.0	-5.7	-10.5	0.2	-19.8	-6.2	0.1	-7.3
Czech Republic	-94.1	0.4	-92.0	-12.1	2.6	-12.5	-158.5	36.1	-274.0	-107.6	-10.3	-119.1
Denmark	-1097.9	-0.6	-962.4	-48.4	16.8	-45.9	-180.3	29.1	-300.0	-305.4	-37.1	-335.3
Estonia	-27.8	0.4	-26.6	-2.9	1.3	-4.2	-47.1	17.8	-90.4	-36.6	2.2	-44.6
Finland	-83.2	-0.5	-74.7	-18.0	-1.9	-21.7	-152.4	-1.0	-272.6	-129.9	-17.1	-166.3
France	-1283.2	6.0	-1173.6	-149.8	15.3	-168.4	-1895.3	186.2	-3158.7	-1413.6	-243.2	-1576.1
Germany	-3109.5	1.5	-2495.9	-356.8	82.5	-363.1	-1503.6	965.2	-4134.8	-1046.7	673.3	-1796.5
Greece	-60.1	-0.1	-47.3	-3.8	2.6	-8.7	-68.7	21.8	-192.5	-24.1	-5.8	-99.7
Hungary	-86.6	0.3	-87.1	-26.3	9.1	-38.9	-95.3	10.8	-162.4	-65.6	-10.8	-65.7
Ireland	-321.8	7.9	-242.8	-34.8	17.4	-48.7	-873.1	357.7	-1603.5	-403.9	156.7	-563.0
Italy	-1498.1	4.4	-1214.0	-138.9	65.8	-276.0	-799.8	88.7	-1390.6	-808.6	-144.1	-823.6
Latvia	-14.2	0.0	-13.9	-15.8	-26.5	-10.6	-58.7	-25.7	-112.5	-54.9	-62.2	-53.3
Lithuania	-44.8	0.2	-41.8	-18.5	4.6	-13.0	-116.3	-2.0	-197.5	-83.5	-26.3	-84.1
Malta	-2.0	0.0	-2.1	-0.6	-0.1	-2.2	-2.0	-0.2	-3.6	-2.2	-0.1	-2.5
Netherlands	-1168.2	-1.0	-1004.2	-109.8	17.9	-122.4	-751.8	117.3	-1216.8	-523.6	21.2	-599.5
Poland	-162.0	1.0	-151.6	-28.5	14.6	-32.8	-863.8	350.6	-1588.7	-681.0	152.2	-613.8
Portugal	-260.9	-1.3	-175.8	-12.6	3.7	-16.8	-155.3	114.6	-372.7	-91.7	6.8	-106.8
Romania	-46.9	0.0	-27.9	-0.7	-1.6	0.9	-203.9	3.0	-54.1	-133.3	-4.9	-26.8
Slovakia	-35.1	-0.0	-6.6	-4.1	0.0	0.0	-35.6	-45.3	-92.5	-29.7	-29.9	-30.2
Slovenia	-7.3	-14.6	-1562.2	0.0	25.8	-83.0	-67.2	30.5	-655.3	-37.7	-13.1	-456.7
Spain	-2008.8	-0.0	-121.8	-47.7	8.5	-36.1	-370.3	61.7	-344.5	-360.0	66.0	-198.2
Sweden	-149.7	1.7	-213.8	-35.8	26.5	-127.4	-202.5	726.0	-2369.8	-172.6	81.1	-993.9
United Kingdom	-416.8	0.5	-46.4	-100.7	-0.3	-2.2	-1338.5	-22.9	-392.5	-795.4	-43.6	-275.9

	Vaccination			Breeding for milk yield		Breeding for ruminant feed efficiency	
	tech only	Overall effect		Overall effect		Overall effect	
		LULUCF	Agric	LULUCF	Agric	LULUCF	Agric
European Union	-7708.3	289.2	-8742.2	-52.7	1916.4	3955.7	-8810.0
Austria	-161.1	5.4	-176.6	-7.6	78.1	96.8	-134.7
Belgium	-200.0	4.1	-223.6	-2.3	31.1	67.4	-186.0
Bulgaria	-47.9	1.1	-53.5	-10.7	48.2	-1.8	-40.2
Croatia	-30.6	1.6	-37.7	-11.4	16.3	3.3	-26.2
Cyprus	-5.0	0.0	-5.6	-0.1	4.5	-0.1	-5.4
Czech Republic	-98.1	3.9	-110.0	-0.9	4.3	26.0	-62.7
Denmark	-186.7	2.7	-205.0	0.3	-3.0	17.8	-82.1
Estonia	-29.9	2.1	-34.9	0.0	0.1	8.3	-19.2
Finland	-98.9	-0.0	-112.0	-1.0	3.7	1.6	-69.6
France	-1682.5	42.6	-1876.9	5.8	311.1	598.7	-2311.4
Germany	-1050.4	42.4	-1167.3	-56.5	285.8	208.1	-832.2
Greece	-53.2	2.1	-65.4	1.2	-5.3	21.1	-139.2
Hungary	-66.4	1.9	-75.4	1.2	8.2	17.1	-51.4
Ireland	-670.9	36.8	-778.2	54.0	313.5	303.2	-641.2
Italy	-484.9	9.0	-529.0	-25.0	262.0	90.2	-294.1
Latvia	-52.0	-0.7	-64.7	-2.3	24.0	9.7	-45.9
Lithuania	-80.3	1.8	-93.7	-5.9	30.9	10.9	-52.1
Malta	-1.2	0.0	-1.4	0.0	0.1	0.0	-0.8
Netherlands	-314.9	4.7	-341.2	-5.2	61.6	35.0	-140.2
Poland	-469.8	23.4	-545.0	-37.6	252.1	99.1	-346.0
Portugal	-135.0	14.1	-167.5	0.2	8.7	87.4	-223.3
Romania	-118.4	0.2	-27.6	-0.5	3.6	4.1	-12.5
Slovakia	-26.3	-0.5	-38.7	-0.9	5.0	-21.3	-104.3
Slovenia	-33.2	21.6	-624.0	-6.3	37.0	1506.2	-1700.7
Spain	-504.2	2.7	-174.5	-2.2	16.2	31.3	-114.9
Sweden	-156.1	65.0	-1079.7	-1.3	55.0	719.4	-1076.9
United Kingdom	-950.5	1.1	-132.9	62.3	63.8	16.0	-97.0

Tech only = the mitigation directly achieved by the specific technological mitigation option. LULUCF and Agriculture = overall mitigation in the respective CRF sectors for each (maximum share) scenario. Note: the 'tech only' mitigation effects linked to the breeding measures 'milk yields' and 'ruminant feed efficiency' cannot be reported in isolation, i.e. only the overall effects can be indicated.

The size of the effects on GHG emissions follows both from the effectiveness of each measure and its implementation share. As defined in the scenario setting, all livestock related measures are implemented up to their maximum share possible in the respective scenario (Table 13). When looking at the implementation shares, the underlying CAPRI assumptions for each technological mitigation option have to be kept in mind (cf. section 3.2).

- For anaerobic digestion, the maximum application share is restricted by farm size, as it is assumed that only farms with more than 200 livestock units can implement this measure.
- The measure low nitrogen feed aims to reduce the over-supply of CRPR intake of animals and hence the upper bound for its implementation is related to the CRPR over-supply in a region.
- The intake of linseed as feed additive depends on the fat content of the diet, which varies between regions.
- The application of nitrate as feed additive is limited to the time of lactation of dairy cows and to a maximum of 1.5% of total dry matter intake.
- For low nitrogen feed and both feed additives (linseed, nitrate) the application is also restricted by the animal types and grazing shares (i.e. the grazing time spent outside the stable).

Accordingly, the different amounts in the absolute GHG emission mitigation achieved at MS level in each scenario in Table 12 depend on the size of the livestock sector and animal population targeted as well as the upper bounds for the implementation of the technology (Table 13). The upper bounds are directly related to both the CAPRI assumptions for each measure and the endogenously calculated regional differences regarding, for example, CPRP over-supply or fat content of the animal diet in the baseline. The zero maximum share of low nitrogen feed in Slovenia implies that excess protein consumption is already close to zero in this country in the baseline. This absence of excess protein consumption in Slovenia, however, more likely reflects unclear data problems rather than an extremely high feeding efficiency.

Table 13. Implementation shares and upper bounds of implementation shares of livestock sector related mitigation measures (one scenario for each measure)

	Anaerobic digestion		Low nitrogen feed		Feed additive: linseed		Feed additive: nitrate		Breeding for milk yield		Breeding for ruminant feed efficiency		Vaccination	
	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound	Simulated share	Upper bound
European Union	35%	35%	54%	54%	28%	28%	42%	42%	100%	100%	100%	100%	100%	100%
Austria	14%	14%	63%	63%	29%	29%	47%	47%	100%	100%	100%	100%	100%	100%
Belgium	45%	45%	66%	66%	27%	27%	38%	38%	100%	100%	100%	100%	100%	100%
Bulgaria	7%	7%	47%	47%	35%	35%	43%	43%	100%	100%	100%	100%	100%	100%
Croatia	10%	10%	59%	59%	31%	31%	42%	42%	100%	100%	100%	100%	100%	100%
Cyprus	55%	55%	56%	56%	41%	41%	43%	43%	100%	100%	100%	100%	100%	100%
Czech Republic	34%	34%	62%	62%	34%	34%	45%	45%	100%	100%	100%	100%	100%	100%
Denmark	72%	72%	91%	91%	21%	21%	58%	58%	100%	100%	100%	100%	100%	100%
Estonia	36%	36%	68%	68%	32%	32%	48%	48%	100%	100%	100%	100%	100%	100%
Finland	23%	23%	67%	67%	32%	32%	51%	51%	100%	100%	100%	100%	100%	100%
France	20%	20%	47%	47%	22%	22%	37%	37%	100%	100%	100%	100%	100%	100%
Germany	52%	52%	56%	56%	32%	32%	43%	43%	100%	100%	100%	100%	100%	100%
Greece	23%	23%	22%	22%	28%	28%	34%	34%	100%	100%	100%	100%	100%	100%
Hungary	31%	31%	68%	68%	29%	29%	39%	39%	100%	100%	100%	100%	100%	100%
Ireland	18%	18%	31%	31%	25%	25%	27%	27%	100%	100%	100%	100%	100%	100%
Italy	44%	44%	73%	73%	35%	35%	63%	63%	100%	100%	100%	100%	100%	100%
Latvia	10%	10%	58%	58%	24%	24%	43%	43%	100%	100%	100%	100%	100%	100%
Lithuania	21%	21%	60%	60%	29%	29%	41%	41%	100%	100%	100%	100%	100%	100%
Malta	56%	56%	77%	77%	33%	33%	58%	58%	100%	100%	100%	100%	100%	100%
Netherlands	64%	64%	76%	76%	38%	38%	47%	47%	100%	100%	100%	100%	100%	100%
Poland	8%	8%	49%	49%	40%	40%	57%	57%	100%	100%	100%	100%	100%	100%
Portugal	59%	60%	48%	48%	23%	23%	37%	37%	100%	100%	100%	100%	100%	100%
Romania	11%	11%	11%	11%	37%	37%	44%	44%	100%	100%	100%	100%	100%	100%
Slovakia	40%	41%	63%	63%	28%	28%	42%	42%	100%	100%	100%	100%	100%	100%
Slovenia	7%	7%			41%	41%	55%	55%	100%	100%	100%	100%	100%	100%
Spain	58%	58%	61%	61%	11%	11%	33%	33%	100%	100%	100%	100%	100%	100%
Sweden	27%	27%	57%	57%	27%	27%	46%	46%	100%	100%	100%	100%	100%	100%
United Kingdom	14%	14%	36%	36%	27%	27%	36%	36%	100%	100%	100%	100%	100%	100%

4.3 Technological options with exogenous model implementation

In addition to the standard case of endogenous mitigation modelling (i.e. the adoption of a mitigation option is a model outcome), we investigate two scenarios with an exogenous implementation of technological mitigation options (i.e. the adoption of a mitigation option is predetermined and enforced upon the model). This concerns 'improved cow longevity' and 'conversion of agricultural land' (cr. section 3.4). In the first case we want to assess the general potential and market effects of this measure as an option to decrease non-CO_2 emissions in the livestock sector. In the second case, we want to test the possibility to account for exogenously determined (e.g. policy induced) afforestation or conversion of cropland to grassland in CAPRI. Thus, when looking at the results of these two complementary scenarios it has to be kept in mind that the scenario setting is quite different compared to other scenarios in this chapter, where we were testing the maximum possible mitigation potential of each measure, without accounting for possible market effects.

4.3.1 Improved cow longevity

The non-linearity of the supply system of CAPRI has prevented the implementation of 'improved cow longevity' as an endogenous technological mitigation option (cf. section 3.4.1). Therefore, in EcAMPA 3 an exogenous implementation of this measure is tested, assuming a 25% decline in the replacement rate of cows (and the associated beef yields) without any other supplementary changes, like for example increased veterinary costs or reduced milk yields that might come along with increased cow longevity. Moreover, no attempt has been made to look for empirical evidence about the magnitude and the circumstances under which such a measure of 'improved cow longevity' would be viable. Consequently, this measure needs to be regarded within a sensitivity analysis context. Differently than in the scenarios presented in section 4.2, in here market effects are taken into account, because market clearing for European young animal markets is handled in the global market model in CAPRI. The same scenario run without market clearing would only yield additional net exports of "excess" young cows to non-European regions with limited other impacts.

A 25% reduction of the replacement rate brings about a significant restructuring within the female cattle activities whereas the activities related to male animals and also the dairy cow herd are hardly changing (Table 14).

Table 14. EU activity levels, agricultural emissions per (cattle) head, and total agriculture emissions following an exogenous 25% reduction in the replacement rate of cows (EU-28, 2030)

	Activity level		Agriculture emissions per head		Agriculture emissions from activities		
		diff to REF		diff to REF		diff to REF	
	1000 hd*	%	kg / hd*	%	1000 t	%	1000 t
Dairy Cows high yield	10262	0.1%	5975	0.2%	61315	0.3%	188
Dairy Cows low yield	10285	0.3%	4787	0.1%	49234	0.4%	219
Other Cows	13155	1.6%	2921	0.2%	38422	1.7%	658
Heifers breeding	5902	-24.0%	3301	0.8%	19481	-23.4%	-5965
Heifers fattening high weight	2378	22.0%	2469	-0.9%	5871	20.9%	1017
Heifers fattening low weight	2607	33.7%	1076	-2.1%	2805	30.9%	662
Male adult cattle high weight	4416	1.2%	2666	0.2%	11772	1.3%	156
Male adult cattle low weight	4401	0.8%	1259	0.2%	5541	1.0%	56
Raising male calves	8817	1.0%	1055	0.2%	9300	1.2%	108
Raising female Calves	10887	-6.7%	1025	0.2%	11163	-6.5%	-781
Fattening male calves	5501	0.5%	590	0.4%	3247	0.8%	27
Fattening female calves	3106	40.6%	673	-4.1%	2091	34.8%	540
All cattle activities	56435	-2.6%	3903	1.2%	220243	-1.4%	-3116
All agricultural activities					421930	-0.9%	-3643

* hd= head. For 'all cattle activities' heads are weighted with livestock units and process length

The level of breeding heifers declines by 24%, which is a bit less than the 25% due to a small increase of the suckler cow herd. The latter is due to the fact that the prices for young heifers are strongly declining whereas on the output side only the price for female calves is dropping (the revenues from male calves are rather stable). With a basically constant cow herd, the number of female calves born is also basically stable. As an important outlet for them (heifers breeding) is shrinking, these female calves are used for intensive fattening activities which are: fattening of female calves (+41%), fattening of low weight heifers (+34%) and fattening of heavy (high weight) heifers (+22%). The expansion of these activities partly counterbalances the intended GHG emission savings of this measure. However, overall, the average lifetime of female cattle declines with 'heifers breeding' replacing 'heifers fattening' and, therefore, slaughtering happens at a younger age.

The ordering in the agricultural GHG emissions per animal is also shown in Table 14, illustrating that emissions per animal decline when moving from heifers breeding (3,301 kg CO_2eq/head) towards fattening of female animals, in particular with lower slaughter weights (673 kg CO_2eq/head for fattening of female calves). At the same time, the table also illustrates that these GHG emissions per animal hardly change as they have not been specifically targeted in the scenario specification. The small changes we see are mostly due to regional composition effects. Combining the changes in activity levels with the (almost unchanged) emission coefficients per animal gives the total GHG emissions caused by the restructuring of the cattle sector. They are supplemented with some additional savings from reduced fodder demand (reallocation from intensive to extensive grassland) to give a total reduction in GHG emissions from agriculture of 3.6 Mt CO_2eq.

The non-CO_2 emission reductions from agriculture are accompanied by additional LULUCF effects. The restructured cattle sector triggers a reduction in fodder area, in particular for pastures and meadows of about 164,200 ha (Table 15).

Table 15. Key land use changes following an exogenous 25% reduction in the replacement rate of cows (EU-28, 2030)

	REF	Scenario Improved Cow Longevity	
		change to REF	
	1000 ha	1000 ha	%
Forest land	158957	19.8	0.01%
Agricultural area	179545	-151.5	-0.08%
Cropland (permanent or temporary crops)	120200	12.8	0.01%
Grassland (incl some shrubland) [of which:]	91039	-66.3	-0.07%
Productive grassland (permanent pastures and meadows)	59345	-164.2	-0.28%
Other land* [of which:]	55892	133.2	0.24%
Residual land (= other land in IPCC terms)	13101	19.7	0.15%

* Other land than agricultural land, forest land, inland waters or artificial areas

Given the current parameterisation in CAPRI, the larger part of the decline in productive grassland would increase "other land" (+133,200 ha) which is estimated to mostly become "shrubland", i.e. the unproductive part within the UNFCCC category 'grassland', which therefore declines less (66,300 ha) than the decline in productive pastures and meadows. However, a minor reallocation towards forestry (+19,800 ha) may be observed as well, which contributes to the total LULUCF-related carbon effects presented in Table 16).

Table 16. Main LULUCF effects (top 8 out of 36 land transitions) following an exogenous 25% reduction in the replacement rate of cows (EU-28, 2030).

	Scenario Improved Cow Longevity		Change to REF		
	Area	Total GLUC	Area	Total GLUC	
	1000 ha	1000 t	1000 ha	1000 t	%
Cropland converted to forest land	57.1	-11192	0.3	-66.3	0.6%
Grassland converted to forest land	106.5	-11260	0.6	-79.8	0.7%
Grassland converted to cropland	380.3	41190	0.7	75.1	0.2%
Cropland converted to grassland	411.4	-38748	-0.8	76.4	-0.2%
Residual land converted to grassland	33.4	-10987	-0.3	102.6	0.9%
Forest land remaining forest land	158739.5	-358746	19.0	-31.4	0.0%
Cropland remaining cropland	119749.9	26639	12.3	329.9	1.2%
Grassland remaining grassland	90496.2	1189	-65.4	250.6	21.1%

The most important CO_2 effects are not due to changes in land allocation but indirectly from lower feed intake (from a smaller cattle herd) and ultimately the carbon balance for agriculture. These changes explain the sizable increase in emissions in the remaining classes of cropland and grassland (about 329,900 t CO_2eq and 250,600 t CO_2eq, respectively; Table 16), which are mainly due to soil carbon (SOC) losses. Negative effects on SOC also arise from reduced conversion of cropland and residual land to grassland (102,600 CO_2eq and 76,400 CO_2eq, respectively, which are mostly SOC losses) and increased conversion in the opposite direction, i.e. of grassland to cropland (75,100 t CO_2eq). These three transitions plus the major SOC losses from two remaining classes mentioned in Table 16 (i.e. last two rows) give the largest part of the total loss related to soil carbon of almost 1 million t CO_2eq shown in Table 17.

These negative effects would be partly compensated by afforestation (i.e. cropland and grassland converted to forest land), including the long run effects on an increasing area of forest land remaining forest land, which both mainly increase the gains from CO_2 sequestration in biomass (-137 600t CO_2eq). The overall effect from the LULUCF sector would be an increase in emissions (i.e. decrease in carbon sequestration) of more than 0.8 Mt CO_2eq. This increase in LULUCF emissions, however, is still lower than the decrease in agriculture emissions of over 3.6 Mt CO_2eq. Accordingly, given our scenario setting, a 25% reduction in the replacement rate of cows at EU-28 level would be favourable in terms of total emission savings.

Table 17. Total GHG emission effects following an exogenous 25% reduction in the replacement rate of cows (EU-28, 2030)

	REF	Change to REF	
	(1000 t CO_2eq)	(1000 t CO_2eq)	%
Agriculture emissions	**425573**	**-3643.4**	**-0.9%**
Methane emissions from enteric fermentation	181093	-2052.3	-1.0%
Methane emissions from manure management (housing and storage)	31887	-141.1	-1.1%
N2O emissions from manure management (housing and storage)	22014	-242.9	-1.1%
Indirect N2O emissions from volatilization (manure management)	5316	-61.4	-1.2%
N2O emissions from manure application	32649	-323.0	-1.0%
N2O emissions from grazing	24777	-414.8	-1.7%
LUC related emissions	**-336422**	**819.5**	**+0.2%**
CO2 emissions from losses of carbon in biomass and litter	-370902	-137.6	0.0%
CO2 emissions from soil carbon losses	-13256	995.9	+7.5%

4.3.2 Conversion of agricultural land

Afforestation and the conversion of cropland to grassland are promising measures to improve LULUCF-related carbon effects. Based on the carbon accounting established in this report, CAPRI can cover the effects that such a (policy induced) afforestation or other land conversion would comprise. To test the main impacts of such an exogenously determined land conversion, a scenario that assumes an additional afforestation of 1% is presented. This is modelled in CAPRI as an exogenous shift from agricultural land to forest land.

Table 18 shows that a non-negligible part of the area for net afforestation (i.e. additional forest land) is supplied by changes of other land and settlement areas, depending on the country. This effect happens even though the scenario specification aims at a direct shift from agricultural area to forest land to restore the total area balance. Similar endogenous adjustments are for example also observed in consumer preference shift scenarios, when the exogenous shift in demand functions usually differs from the final (endogenous) simulation result.

Apart from the fact that non-agricultural land use also contributes to re-establishing the area balance in this scenario, Table 18 also shows that the achieved net afforestation (+0.68% in EU-28) usually falls somewhat short of the target (+1% increase in forest area). This is in line with agricultural rents increasing by about 2% compared to the reference for the EU-28 average, i.e. in the simulation the feedback effect of increasing rents of agricultural land prevent that the 1% increase in forest land is reached. Accordingly, a higher conversion share would need to be envisaged in the scenario design in order to actually reach the 1% afforestation goal after market (including land use) adjustments.

Table 18. Land use results from increased afforestation (2030)

	Forest land			Agricultural area			Settlement (Artificial) area			Other land (than forest, agriculture, artificial, waters)		
	1000 ha	abs diff to ref	% diff to ref	1000 ha	abs diff to ref	% diff to ref	1000 ha	abs diff to ref	% diff to ref	1000 ha	abs diff to ref	% diff to ref
European Union	160046	1089	0.7%	178476	-1069	-0.6%	28833	-84	-0.3%	55956	64	0.1%
Austria	3696	22	0.6%	2936	-22	-0.7%	549	-2	-0.4%	1053	2	0.1%
Belgium	758	4	0.6%	1468	-4	-0.2%	749	-1	-0.1%	293	0	0.0%
Bulgaria	3935	26	0.7%	5084	-28	-0.6%	594	-2	-0.4%	1370	5	0.4%
Croatia	2203	16	0.7%	1309	-10	-0.8%	389	-1	-0.3%	1727	-5	-0.3%
Cyprus	182	1	0.6%	127	-2	-1.4%	76	0	-0.4%	531	1	0.2%
Czech Republic	2840	26	0.9%	3684	-27	-0.7%	941	-1	-0.1%	262	2	0.8%
Denmark	644	5	0.7%	2673	-1	0.0%	682	-2	-0.2%	245	-2	-0.9%
Estonia	2405	16	0.7%	919	-22	-2.3%	377	-2	-0.5%	501	8	1.6%
Finland	22591	123	0.5%	2122	-115	-5.1%	1168	-6	-0.5%	4450	-3	-0.1%
France	16564	113	0.7%	28384	-89	-0.3%	4584	-11	-0.2%	4826	-13	-0.3%
Germany	11580	62	0.5%	16583	-72	-0.4%	3678	-18	-0.5%	2857	28	1.0%
Greece	3668	24	0.7%	4823	-29	-0.6%	650	-3	-0.4%	3760	8	0.2%
Hungary	2061	15	0.7%	5476	-17	-0.3%	645	-2	-0.3%	907	5	0.5%
Ireland	876	7	0.8%	4260	-8	-0.2%	131	0	-0.2%	1571	1	0.1%
Italy	9183	60	0.7%	13879	-82	-0.6%	2533	-7	-0.3%	3766	30	0.8%
Latvia	3387	23	0.7%	1943	-30	-1.5%	290	-1	-0.5%	638	9	1.4%
Lithuania	2238	16	0.7%	2847	-17	-0.6%	341	-1	-0.3%	838	2	0.2%
Malta	0	0	0.0%	11	0	0.0%	11	0	0.0%	10	0	0.0%
Netherlands	400	3	0.8%	1820	-2	-0.1%	597	-1	-0.2%	621	-1	-0.1%
Poland	9658	66	0.7%	15624	-83	-0.5%	2460	-8	-0.3%	2840	25	0.9%
Portugal	3440	27	0.8%	3337	-29	-0.9%	650	-2	-0.4%	1673	5	0.3%
Romania	6474	47	0.7%	13479	-48	-0.4%	1745	-5	-0.3%	1330	5	0.4%
Slovakia	2070	12	0.6%	1917	-16	-0.8%	335	-2	-0.4%	507	6	1.2%
Slovenia	1283	9	0.7%	465	-11	-2.2%	97	-1	-0.5%	155	2	1.2%
Spain	16845	99	0.6%	23314	-102	-0.4%	1248	-5	-0.4%	8523	9	0.1%
Sweden	27909	239	0.9%	2787	-176	-5.9%	1815	0	0.0%	8616	-62	-0.7%
United Kingdom	3157	30	0.9%	17207	-28	-0.2%	1498	-1	-0.1%	2090	-1	-0.1%

Note: ref = reference scenario, 2030

The carbon effects of this scenario are mainly determined by the land use transition matrix, which explains land conversions taking place between the six UNFCCC land categories. As explained in section 2.3.3, the transitions between the land categories are assumed to be generated by a stochastic process creating a typical pattern with some transitions being more important (e.g. between grassland and cropland) and others less relevant (e.g. between forest land and settlement area). If the total area of the six land use categories is changing, for example to have forest land increasing, then the whole transition matrix has to change as well to have a consistent land balancing. As the drivers favour some transitions over others (due for instance to natural conditions, geographical proximity, laws and customs), the transition matrix is changed in such a way that 'similarity' to the historical patterns is preserved as good as possible while complying with the new land use totals for the six land categories. The new transitions may be interpreted therefore as the most probable ones, conditional on new land use totals.

Table 19 illustrates that the general carbon benefits of afforestation might be large. Our scenario, with an actual increase in total forest area of 0.68% results in about 13.2 Mt of CO_2 savings in the LULUCF sector, supplemented with a reduction of agriculture GHG emissions of 1.1 Mt CO_2eq, the latter being due to the reduced area. An important finding of the detailed analysis of the main contributors to the large LULUCF benefits has been that the changes in forest area also involve differences in net carbon sequestration from forest management (FM), i.e. use of forests without land use change.

In the standard version of the CAPRI model the FM effects per ha are taken from the latest UNFCCC data, a procedure that can be considered a simplification. To analyse the sensitivity of the LULUCF results to the assumed FM effects per ha, the same scenario is done changing the per ha contributions from FM according to the European Commission's 2016 EU Reference Scenario (cf. European Commission 2016a, p. 209-217). As explained in the respective report, ageing forests and increased wood demand would tend to reduce the net sequestration in the next decades from FM. However, FM is also responsive to GHG emissions mitigation policies embedded in the 2016 EU Reference Scenario. It is, therefore, a simplified assumption to adopt the change in FM contributions from this reference run, but it is at least a reasonable and feasible alternative to the standard 'no change' approach. The following two tables present the LULUCF effects under both the UNFCCC and 2016 Reference Scenario assumptions regarding FM.

As shown in Table 19, switching from the assumptions of stable (i.e. UNFCCC) to declining (i.e. 2016 Reference Scenario) FM contributions can decrease the overall LULUCF benefits in our afforestatrion scenario from 13.2 Mt CO_2eq to 12.2 Mt CO_2eq. The change in the FM assumption does not affect the emissions from agriculture as no carbon price is involved in the scenario at hand (but agriculture emissions may also be affected in scenarios with a carbon price).

Table 19. LULUCF and agriculture GHG emissions from increased afforestation, using per ha coefficients for forest management (FM) from UNFCCC notifications or from the European Commission's 2016 Reference Scenario (1000 t CO_2eq compared to REF, 2030)

	GHG emissions considering effects of			
	FM per ha from UNFCCC		FM per ha from 2016 Reference Scenario	
	LULUCF	Agriculture	LULUCF	Agriculture
European Union	-13298.9	-1071.0	-12244.1	-1072.3
Austria	-249.0	-24.8	-239.9	-24.8
Belgium	-57.8	-8.9	-53.6	-8.9
Bulgaria	-238.8	-20.0	-231.7	-20.0
Croatia	-195.5	-4.8	-173.7	-4.8
Cyprus	-15.1	-1.3	-14.7	-1.3
Czech Republic	-284.1	-26.3	-285.5	-26.3
Denmark	-85.3	-0.2	-78.1	-0.2
Estonia	-162.4	-16.9	-122.4	-16.9
Finland	-2386.1	-227.3	-2267.3	-227.3
France	-1245.5	-107.1	-1007.7	-107.1
Germany	-1015.0	-114.4	-959.3	-115.8
Greece	-216.4	-21.9	-196.8	-21.9
Hungary	-153.7	-13.4	-145.7	-13.4
Ireland	-61.2	-20.4	-42.7	-20.4
Italy	-716.7	-45.4	-646.5	-45.4
Latvia	-312.2	-17.9	-263.1	-17.9
Lithuania	-211.9	-8.8	-227.5	-8.8
Malta	0.0	0.0	0.0	0.0
Netherlands	-39.9	-2.4	-32.0	-2.4
Poland	-1010.4	-60.9	-884.1	-60.9
Portugal	-255.8	-16.6	-219.6	-16.6
Romania	-550.1	-26.4	-442.5	-26.4
Slovakia	-153.3	-10.9	-152.9	-10.9
Slovenia	-111.6	-9.2	-91.6	-9.2
Spain	-962.7	-59.0	-968.2	-59.0
Sweden	-2192.1	-173.7	-2139.1	-173.7
United Kingdom	-416.3	-32.2	-358.1	-32.2

In Table 20 the 10 most important land transitions that explain 99% of the total EU-28 LULUCF effects from Table 19 are presented. The most important emission effects come from:

- conversion of cropland and grassland to forest land (afforestation),
- reduced conversion from forestry to cropland and grassland (less deforestation),
- reduced emissions from cropland (declining use of histosols for cropland),
- forest management (continued sequestration of carbon under growing forests).

The effects of reduced emissions from cropland and FM may be surprising, as Table 20 shows that the areas of 'cropland remaining cropland' and 'forest land remaining forest land' are changing significantly. This is due to the fact that increased afforestation and less deforestation in the period 2010-2030 would accumulate to change the total areas in 2030 as planned in the scenario. The carbon effects, however, are only computed on an annual basis (for the last year) to comply with the computation of non-CO_2 emissions from agriculture in CAPRI, which is done on an annual basis.

The apparently contradictory possibility to have changes in the remaining land use classes as well as the comparability with annual non-CO_2 effects is critical and worth an extended example (see box below).

Example: land use changes over time and annual carbon accounting in CAPRI

Assumptions:

- We assume a country that in 2010 has 200,000 ha of forest land and 200,000 ha of cropland, and by 2020 forest land has declined to 100,000 ha due to conversion of forest land to cropland (= FORCRP transition).

- We assume a forest support policy that reverts this trend in 2020, ending deforestation and creating afforestation from cropland instead (= CRPFOR transition) by 2030.

- We assume that other land uses are not interacting with cropland or forest land.

Land use changes

If we approximate the geometric matrix type growth path of the Markov chain embedded in CAPRI linearly, in 2019 we would have 110,000 ha of forest land (i.e. 10,000 ha are shifted from forest land into agricultural land per year between 2010 and 2020). Of those, 100,000 ha would remain forest (= FORFOR transition) and 10,000 ha would be converted to cropland (= FORCRP transition). Cropland would have grown to about 290,000 ha in 2019 and all of this should remain cropland, such that CRPCRP = 290,000 ha in 2020.

Under the forest support policy, cropland is assumed to decline by 2029 to 110,000 ha and forest land to increase to 290,000 ha. By 2030 we could have then 100,000 ha of cropland remaining (= CRPCRP transition), 10,000 ha afforested (= CRPFOR transition) and 290,000 ha of forest land remaining (= FORFOR transition).

Consequently we compute from the comparison of "forest support" and "reference policy": delta(FORFOR) = 290,000-100,000 = 190,000 ha, delta(CRPCRP) = 100,000–290,000 = -190,000 ha, delta(CRPFOR) = 10,000–0 = 10,000 ha, etc.

Note that the remaining land use transitions are changing in the scenario due to the accumulation of previous annual changes.

Carbon accounting

For carbon accounting, CAPRI takes the effects from the last simulation year. The calculation of average land transitions and carbon effects (in this example for the decade 2010-2020) would be more complicated. Note that the carbon effects from land use change over a whole decade are still only computed for 2020. They are, therefore, annual changes for 2020 and can be aggregated with non-CO2 emissions. This is important in the case of a scenario where a carbon price is applied to the whole AFOLU sector (CAPRI codes: GWPA+GLUC), so that an economically efficient outcome is obtained.

Results in Table 20 are presented both for the standard assumption on FM, i.e. maintaining the coefficients from the most recent UNFCCC notifications, or as a sensitivity check, adopting the change in these coefficients from the European Commission's 2016 Reference Scenario. It can be seen that reduced net sequestration coefficients from FM would indeed reduce the total gains from FM by about 1 Mt CO_2eq, as explained above (i.e. difference between the last two rows for the LULUCF total effects in Table 20). Nonetheless, a gain of 1.3 Mt CO_2eq would still remain even under the 2016 Reference Scenario assumptions with decreased net sequestration per ha. It has to be noted that an accounting based on the default IPCC recommendations would assume that forests are in an equilibrium and net sequestration can be ignored.

It may also be noted that small reallocations of residual land (1,000 ha at EU-28 level in our test scenario) can trigger rather big effects because the current default assumption in CAPRI is that residual land has zero soil organic carbon, which is lost or gained in transitions. In our scenario the conversion of residual land to forest land implies a GHG emissions reduction of 414,000 t CO_2eq. It may also be observed that any transitions involving forestry, even when small in terms of areas involved, tend to give major carbon effects (e.g. when converted to cropland, grassland, artificial land). Finally we may note that the transitions between cropland and grassland, which are typically among the largest in the baseline, are also relevant in scenarios where they are not directly targeted (as in this test scenario). This is because restoring the total area balance in the model runs after any shock often involves some resizing of these major land use changes.

Table 20. Most important LULUCF effects from increased net afforestation in EU-28 (compared to REF, 2030)

	Area [kha]	Biomass and litter (CO2BIO) [kt CO2eq]	Soil carbon (CO2SOI) [kt CO2eq]	Organic soils (CO2HIS) [kt CO2eq]	LULUCF total (GLUC) [kt CO2eq]
Cropland converted to forest land	15	-1731	-1195	0	-3032
Grassland converted to forest land	18	-2211	222	0	-1963
Residual land converted to forest land	1	-113	-275	0	-414
Forest land converted to cropland	-2	-331	-178	-7	-532
Grassland converted to cropland	-7	-112	-640	-1	-818
Forest land converted to grassland	-6	-1054	95	0	-949
Cropland converted to grassland	8	-195	-441	0	-677
Forest land converted to artificial area	-5	-737	-180	0	-934
Cropland remaining cropland	-754	0	-254	-997	-1252
Forest land remaining forest land (FM per ha from recent UNFCCC)	1050	-2382	0	0	-2354
Forest land remaining forest land (FM per ha from 2016 Reference Scenario)	1050	-1327	0	0	-1300

Note: FM = forest management coefficients

5 Marginal abatement cost curves

In this chapter we set the level of GHG emissions mitigation achieved by the technological mitigation options in relation to the associated costs. Section 5.1 outlines some general remarks on marginal abatement costs (MAC), marginal abatement cost curves (MACCs) and the scenario settings we use to generate them. Sections 5.2 and 5.3 present the calculation of MACCs in CAPRI following a 'standalone measures' and a 'combined measures' approach, respectively, and discuss the main results.

5.1 General remarks on marginal abatement costs, marginal abatement cost curves and scenario settings

The 'marginal abatement cost' is the cost of mitigating an additional unit of emissions compared to a reference level of emissions. Accordingly, the total cost of mitigation is the sum of the marginal costs. A MACC in the context of climate change mitigation is an accounting methodology used to graphically rank the cost-effectiveness of different GHG emission mitigation measures. Depending on how mitigation technologies are implemented, two different approaches to construct MACCs are presented:

— *Standalone measures approach* (section 5.2): Each technological mitigation option is implemented in isolation, without considering interactions with other measures. Moreover, it is assumed that each option is adopted to its maximum share possible, independently of the costs incurred (cf. chapter 4).

— *Combined measures approach* (section 5.3): Each technological mitigation option is implemented cumulatively and interactions between the measures are taken into account. In this case, several scenarios with different levels of carbon prices are constructed such as to analyse how mitigation options are adopted by farmers to reduce emissions depending on the costs incurred.

In general, MACCs allow for a direct comparison of different mitigation options. Due to the dual manner in which we construct our MACCs, we use different ways for the graphical representation of the MACCs depending on whether the standalone or combined measures approach is taken.

Graphical representation of the two approaches

In the presentation of the standalone measures approach, each bar in the MACCs represents a different technological mitigation option. The width of the bar represents the mitigation potential (Mt CO_2eq) and the height of the bar represents unit costs (EUR/t CO_2eq mitigated). Measures are ranked according to costs. Ranking abatement measures and actions in this way is appealing as it allows pointing at measures that offer the greatest mitigation benefits and at which cost. For instance, it might be used by policy makers to support financially or enforce a specific measure based on these parameters (e.g. as part of the CAP).

However, the ranking in this representation has to be taken with caution as it assumes a theoretical maximum application of each mitigation measure, and does not consider possible interactions between the different measures. Consequently, the mitigation achieved by each measure cannot be added to obtain a cumulative total mitigation potential. In the CAPRI context, for example, nitrification inhibitors and precision farming should not be combined because the former is implied in the latter. We also assume that feed additives and anti-methanogenic vaccination cannot be combined in the modelling because their combined effect is largely unknown. In a linear programming framework without constraints across technologies it may be that technologies would be fully implemented up to their technological capacity according to costs per t CO_2eq, but the possibility to draw conclusions on the total mitigation potential of a set of ranked mitigation options is generally limited.[27]

As a way to overcome these limitations, we also present scenarios on mitigation technology adoption following a combined measures approach. The scenario setting for this approach is different as we run scenarios with different carbon prices (i.e. mitigation efforts) with all mitigation technologies available. Their implementation is, therefore, not prescribed but the result of the decision of the economic agents in the model. In the case of these MACCs, we present for each carbon price scenario the mitigation achieved per technology, adding up to the combined (cumulative) total mitigation, represented as the height of the bar. The related costs are shown as the average MAC for combined (i.e. total) technology adoption per scenario instead of MAC per technology.

While the standalone measures approach allows us to assess the theoretical maximum emissions mitigation potential per technology, the combined approach allows demonstrating how each technology could contribute to the total mitigation under a set of mitigation policy scenarios. In both approaches the costs include the accounting costs of implementing the technology and an approximation of the transaction costs for non-adoption of theoretically cost-effective technologies (for example, absence of information about the benefits of a specific measure by farmers or reluctance to change current management practices; cf. section 3.5).

5.2 Marginal abatement cost curves calculated following a standalone measures approach

In this section we calculate national and aggregated EU MACCs through a series of scenarios where technological GHG emission mitigation options are applied in the EU farming sector in year 2030. As in chapter 4, all scenarios are 'maximum adoption share' scenarios. Thus, the decision of adopting a certain mitigation technology is not incentivised, for example by the payment of a specific subsidy or triggered by a carbon tax, but imposed by design, i.e. each mitigation technology is applied to the maximum share possible. However, as costs were not analysed in chapter 4, in this section we set the maximum level of emissions mitigation achieved by each technology into perspective with the associated costs.

This approach to construct MACCs allows us to rank different technological emissions mitigation options in terms of their theoretical maximum mitigation potential and the costs attached to each emission unit abated. The mitigation indicated in the graphs for each mitigation option corresponds to the 'tech only' columns in Table 10 and Table 12.

How to read the MACCs in this section:

- Each bar in the MACCs represents a different technological mitigation option.
- The height of a bar represents the unit cost of the mitigation option in Euro per tonne of CO_2eq emissions mitigated. The costs are average unit costs if the mitigation option is implemented to the maximum possible share.
- All measures are ranked according to their unit costs, with the least costly on the left.
- The width of a bar represents the maximum abatement potential of the measure in million tonnes of CO_2eq emissions mitigated.
- The area of a bar represents the total cost of the mitigation achieved by the measure.

As mentioned above, in this scenario set-up farmers are forced to adopt the respective mitigation technology to the maximum possible share. As described in section 3.5, the way CAPRI models the adoption of mitigation options considers that the costs of adoption are

[27] The lack of consideration of these elements is a general critique of bottom-up technological MACCs (see, for example, De Cara and Jayet (2011); Kesicki and Ekins 2012; Eory et al. 2018).

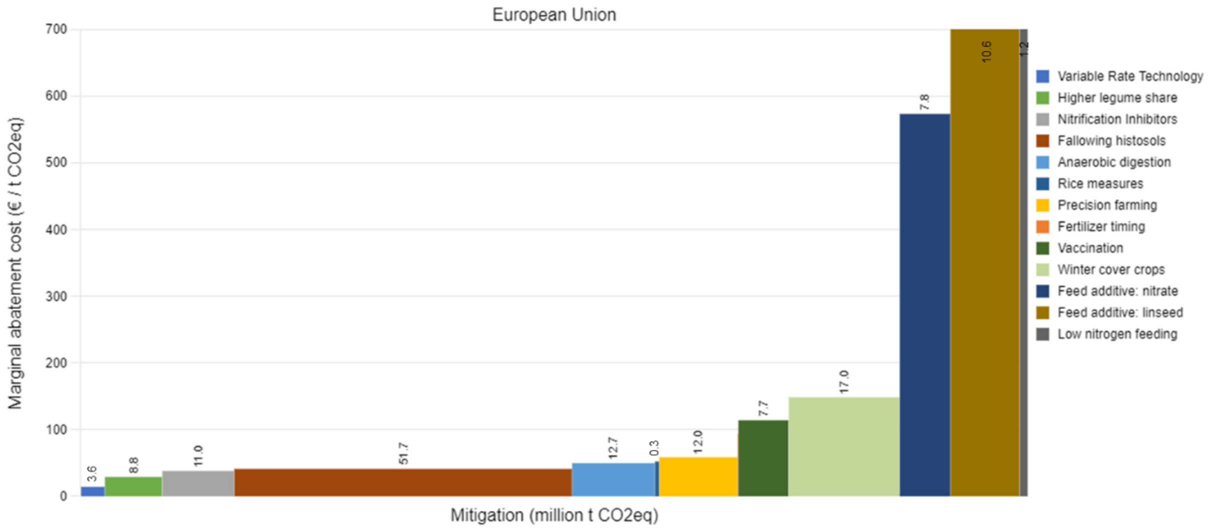
increasing with the share of farmers (regions) that adopt the measure. This reflects the fact that early adopters might only face the pure accounting costs of a measure (i.e. the ones considered in the databases), whereas further adopters face additional costs related to the determinants of technology adoption going beyond pure profitability considerations (cf. section 3.5). As we assume here maximum implementation of each mitigation technology, the MACCs presented include all adopters, those with relative low adoption costs (accounting costs + additional costs) and those with relative high adoption costs. The reported costs represent the average over all adopters.

From the analysis of the results for the EU-28, measures can be clustered into four groups (Figure 9):

1. *High mitigation & relatively low cost:* Measures that are modelled to deliver a high level of mitigation (at EU level this means >10 Mt CO_2eq) or at least a significant level of mitigation (between 3-10 Mt CO_2eq) at relatively low costs (<60 Euro per t CO_2eq abated). This group includes: nitrification inhibitors, fallowing of histosols, anaerobic digestion, and precision farming (high level of mitigation); variable rate technology and higher legume share on temporary grassland (significant level of mitigation).
2. *Low mitigation & relatively low cost:* Measures that are modelled to deliver low levels of mitigation (<1 Mt CO_2eq) at either relatively low costs (<60 Euro per t CO_2eq abated), such as rice measures, or at significant costs (between 60-100 Euro per t CO_2eq abated), such as better timing of fertilizer application.
3. *High mitigation & high cost:* Measures that are modelled to deliver a high (>10 Mt CO_2eq) or at least significant level of mitigation (3-10 Mt CO_2eq) at high costs (>100 Euro per t CO_2eq abated), such as vaccination against methanogenic bacteria in the rumen, winter cover crops, and the two feed additives nitrate and linseed.
4. *Low mitigation & high cost:* Measures that are modelled to deliver low levels of mitigation (<=1 Mt CO_2eq) at high costs (>100 Euro per t CO_2eq abated). These measures would be the lowest in the ranking, and at EU level this group includes low nitrogen feeding.

Measures in group 1 are the most promising in terms of both abatement potential and related costs. Following the EU results, fallowing of histosols appears as the most promising measure in terms of total emission abatement (with a total of more than 50 Mt CO_2eq of mitigation potential). From a marginal abatement cost perspective, however, VRT and higher legume share on temporary grassland appear as most attractive as they have the lowest costs per t CO_2eq abated. Despite its rather low levels of mitigation at aggregated EU level, the rice measures from group 2 can also be worth using, as they are only applicable in the few EU MS that actually have rice production. The measures in group 3 should not be discarded either, because it might be that their relatively high costs are due to enforcing all farmers to apply these measures, i.e. there might be still farmers or regions that could adopt the measures at relatively low costs. In this respect, it has to be kept in mind that the MACs presented per technology are an average, i.e. there are regions (farmers) with lower or higher abatement costs per unit of CO_2eq. We will address this issue in section 5.3 in the scenarios with carbon prices.

Figure 9. EU standalone measures MACC



Notes: Maximum mitigation potential directly achieved by the specific technological mitigation option ('tech only'). The individual mitigation potentials cannot be added up to form a cumulative effect. Including CO_2 emissions: fallowing histosols, higher legume share on temporary grassland, winter cover crops. The y-axis shows marginal abatement costs in the context of a MACC looking at the entire figure, i.e. over all mitigation technologies, when moving from one technology to the next. However, for each technology the height of the bar represents the average costs per tonne CO_2eq abated. The costs for linseed and low nitrogen feeding go beyond 700 €/t CO_2eq.

The group setting used above for the aggregated EU can also be applied at the MS level. While the actual absolute mitigation potential of each measure is naturally smaller in each MS than in the EU aggregate, the grouping still holds in terms of high and low cost measures and regarding the relative terms of high and low mitigation potential.

From a MS perspective, we see a generally similar pattern of the mitigation measures in terms of mitigation potential and costs, but also some differences in the grouping of measures compared to the results obtained for the aggregated EU-28.

— In France (Figure 10), fallowing of histosols becomes the technology with the lowest cost per unit of emissions abated while having at the same time the largest abatement potential. Nitrification inhibitors, higher legume shares on temporary grassland and precision farming also offer a high mitigation potential at relatively low costs (<60 Euro per t CO_2eq abated).

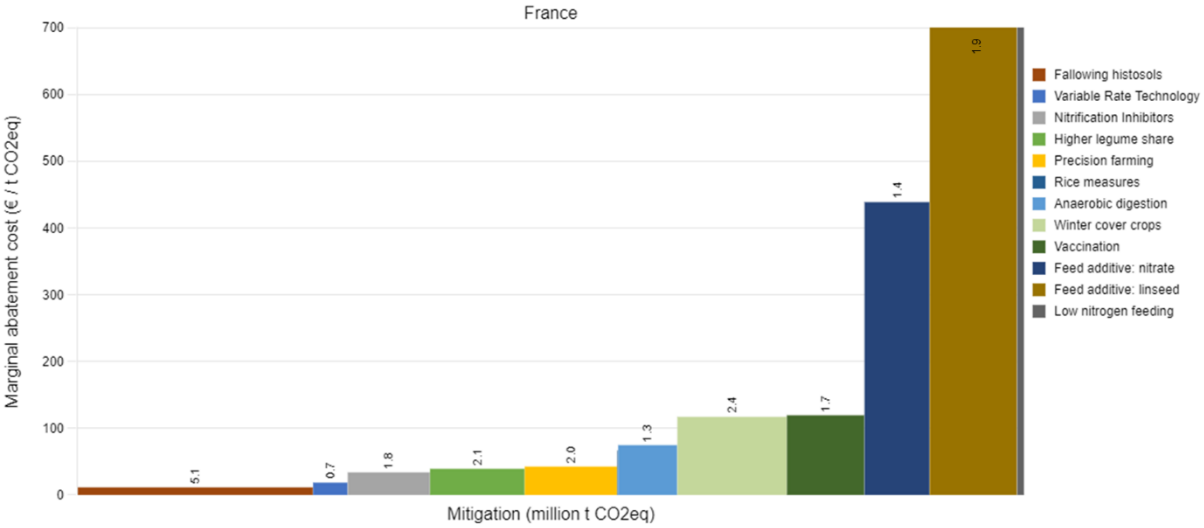
— In Germany (Figure 11) and the UK (Figure 12), fallowing of histosols is the most promising measure in terms of mitigation potential, with also low costs attached (especially in Germany due to high presence of histosols in the country). Anaerobic digestion in Germany is also indicated as having a high mitigation potential at costs below 60 Euro per t CO_2eq abated. In the UK, anaerobic digestion is less promising in terms of mitigation potential whereas other livestock production technologies show a higher emission mitigation potential than in the other countries analysed in this section. However, the related costs for the feed additives and vaccination technologies are still high if all UK farmers would (have to) adopt them.

— Spain (Figure 13) has a considerably lower mitigation potential from fallowing of histosols, which is due to the low presence of histosols in the country. Nonetheless, fallowing of histosols could mitigate almost 0.9 Mt CO_2eq at the lowest costs in Spain. Winter cover crops are much more attractive than in many other MS in terms of relatively low costs and high mitigation potential, and also anaerobic digestion shows a relatively high mitigation potential at lower costs than 60 Euro per t CO_2eq abated.

— In Poland (Figure 14), fallowing histosols is indicated as the most important mitigation technology both in terms of mitigation potential (6.4 Mt CO_2eq) and low costs (about 3 Euro/t). Nitrification inhibitors are as well a promising measure, with an emission abatement potential of 1.6 Mt CO_2eq and costs of about 40 Euro/t. Compared to the EU, precision farming in Poland would move from the first to the third group of measures, with a mitigation potential of 1.8 Mt CO_2eq at relatively high abatement costs of almost 100 Euro/t.

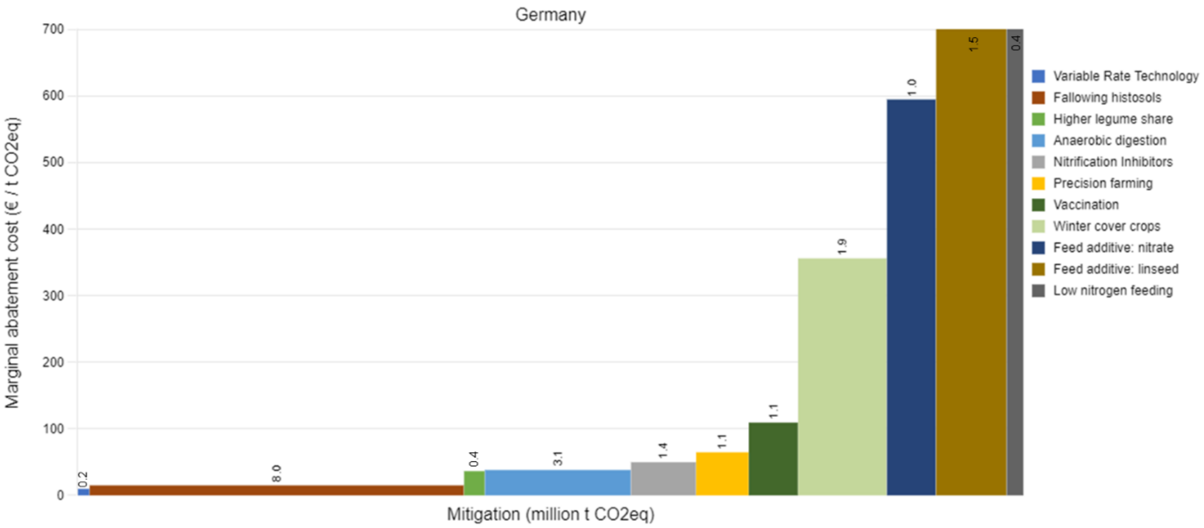
— In Ireland (Figure 15), higher legume shares on temporary grassland could be a relatively cost-effective mitigation option. Nitrification inhibitors and also precision farming still look promising at abatement costs of around 60 EUR/t CO_2eq. Due to the large dairy and sheep herds in Ireland, the livestock measures show the highest mitigation potentials, especially vaccination against methanogenic bacteria in the rumen and linseed as feed additive, but at high abatement costs.

Figure 10. France standalone measures MACC



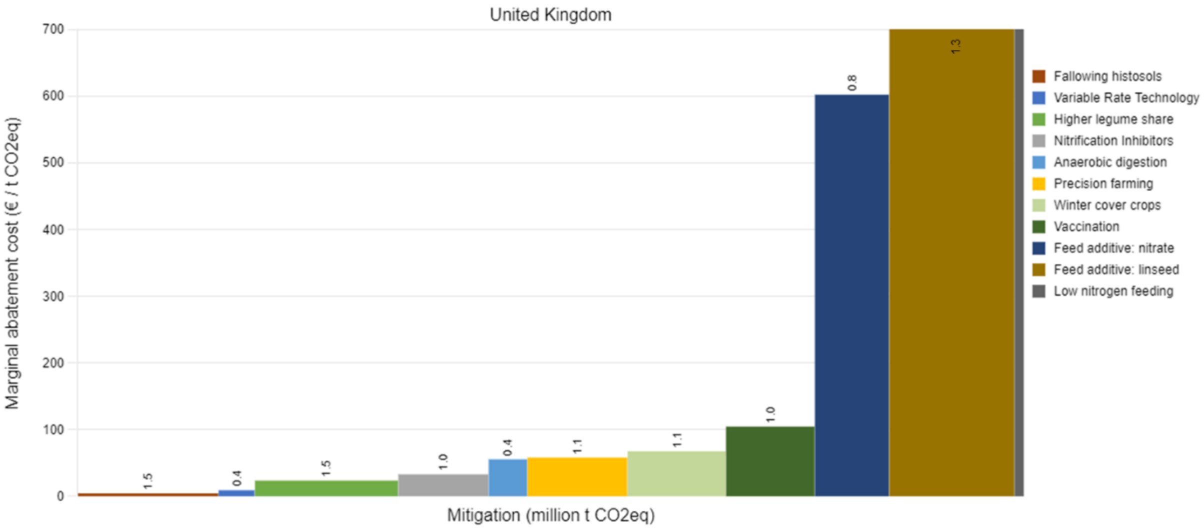
Notes: Maximum mitigation potential directly achieved by the specific technological mitigation option ('tech only'). The individual mitigation potentials cannot be added up to form a cumulative effect. Including CO_2 emissions: fallowing histosols, higher legume share on temporary grassland, winter cover crops. The costs for linseed and low nitrogen feeding go beyond 700 €/t CO_2eq.

Figure 11. Germany standalone measures MACC



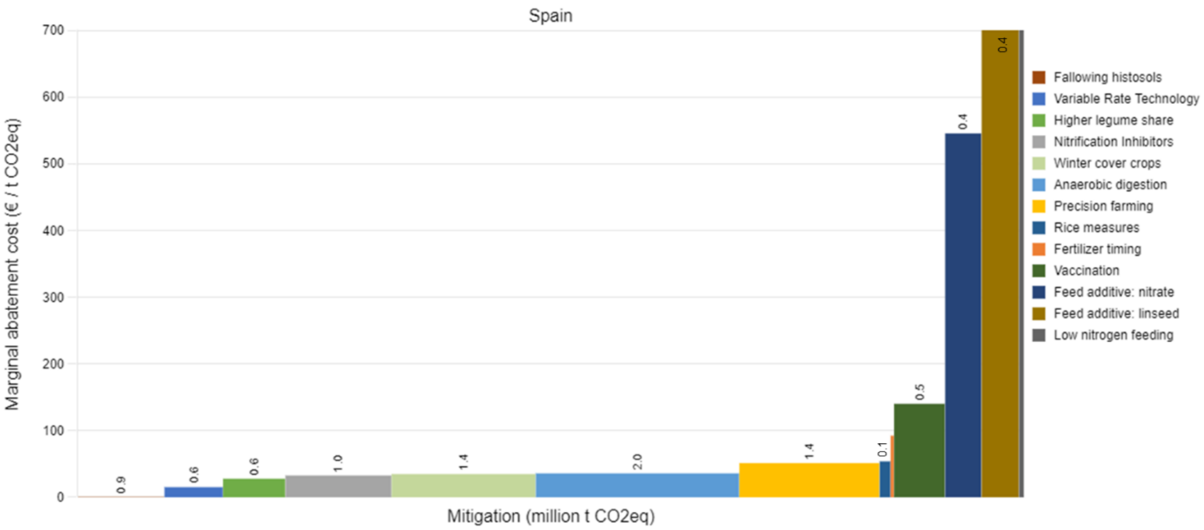
Notes: Maximum mitigation potential directly achieved by the specific technological mitigation option ('tech only'). The individual mitigation potentials cannot be added up to form a cumulative effect. Including CO_2 emissions: fallowing histosols, higher legume share on temporary grassland, winter cover crops. The costs for linseed and low nitrogen feeding go beyond 700 €/t CO_2eq.

Figure 12. UK standalone measures MACC



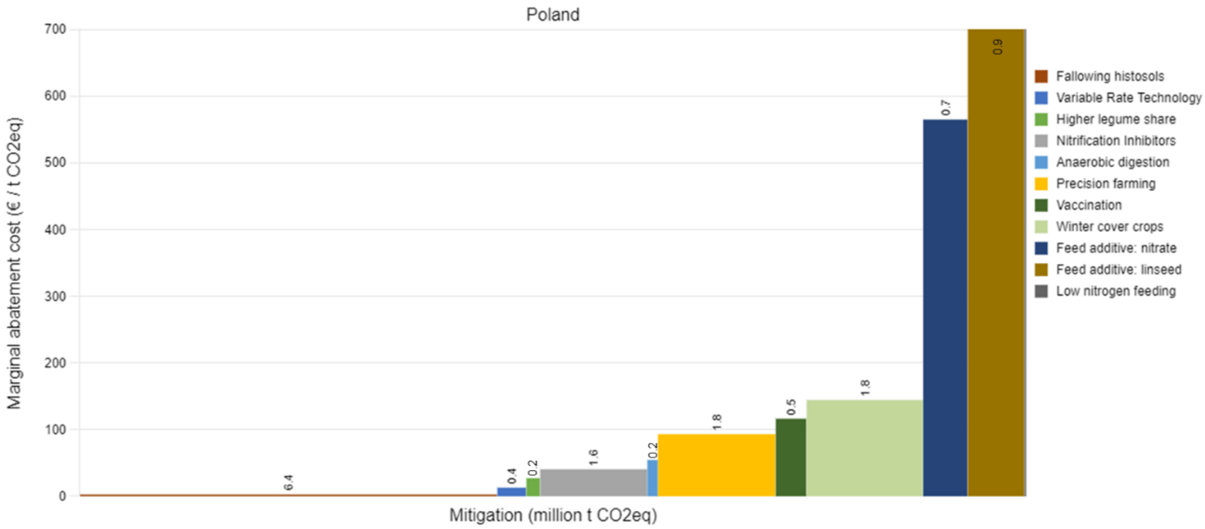
Notes: Maximum mitigation potential directly achieved by the specific technological mitigation option ('tech only'). The individual mitigation potentials cannot be summed up to form a cumulative effect. Including CO_2 emissions: fallowing histosols, higher legume share on temporary grassland, winter cover crops. The costs for linseed and low nitrogen feeding go beyond 700 €/t CO_2eq.

Figure 13. Spain standalone measures MACC



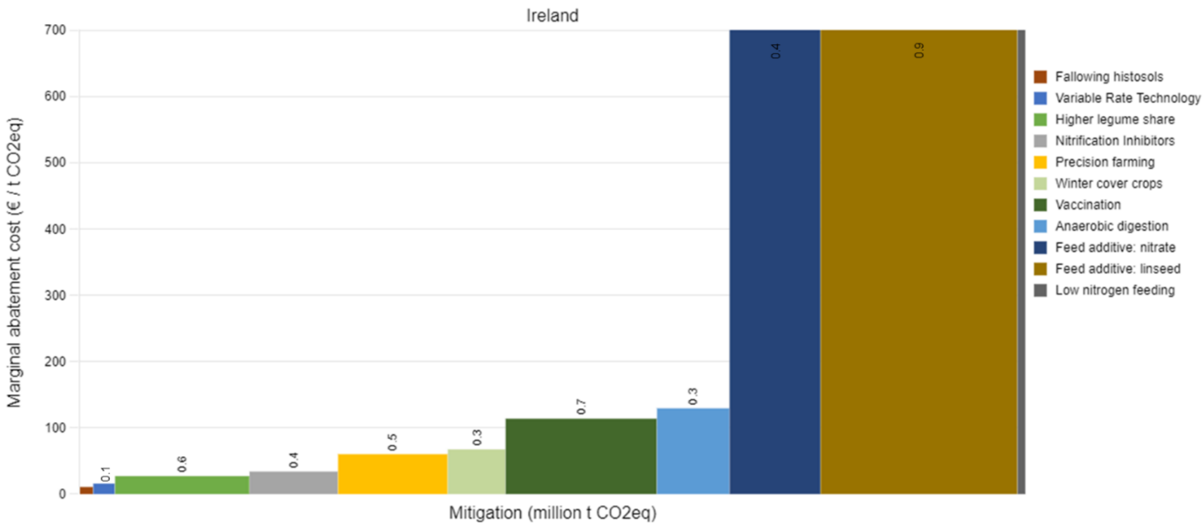
Notes: Maximum mitigation potential directly achieved by the specific technological mitigation option ('tech only'). The individual mitigation potentials cannot be added up to form a cumulative effect. Including CO_2 emissions: fallowing histosols, higher legume share on temporary grassland, winter cover crops. The costs for linseed and low nitrogen feeding go beyond 700 €/t CO_2eq.

Figure 14. Poland standalone measures MACC



Notes: Maximum mitigation potential directly achieved by the specific technological mitigation option ('tech only'). The individual mitigation potentials cannot be added up to form a cumulative effect. Including CO_2 emissions: fallowing histosols, higher legume share on temporary grassland, winter cover crops. The costs for linseed and low nitrogen feeding go beyond 700 €/t CO_2eq.

Figure 15. Ireland standalone measures MACC



Notes: Maximum mitigation potential directly achieved by the specific technological mitigation option ('tech only'). The individual mitigation potentials cannot be added up to form a cumulative effect. Including CO_2 emissions: fallowing histosols, higher legume share on temporary grassland, winter cover crops. The costs for the feed additive (nitrate and linseed) and low nitrogen feeding go beyond 700 €/t CO_2eq.

5.3 Marginal Abatement Cost Curves calculated following a combined measures approach

In contrast to the scenarios analysed in chapter 4 and section 5.2, here a combined measures approach is presented, which means that all technological mitigation options are available at the same time in all scenarios and can be adopted cumulatively by farmers. For this, EU and MS specific MACCs are calculated through a series of mitigation policy scenarios resumed in different EU-wide carbon prices[28]. Accordingly, farmers will adopt each technology depending on the relative costs. Thus, instead of generally classifying mitigation technologies as relatively cheap or expensive options (as in the standalone

[28] Carbon prices in our analysis target only agricultural non-CO_2 emissions (i.e. methane and nitrous oxide emissions) but not CO_2 emissions and sinks. Effects on CO_2 savings are, therefore, only secondary (i.e. side) effects resulting from the carbon price on non-CO_2 emissions.

approach), the combined measures approach allows to classify options regarding their *cost-effectiveness* under the condition of different carbon price levels. In the context of the combined measures approach we consider a technology as cost-effective when it is applied, because it would not be adopted if the unit cost of adoption (in Euro per t CO_2eq) would outweigh the costs of the carbon price.

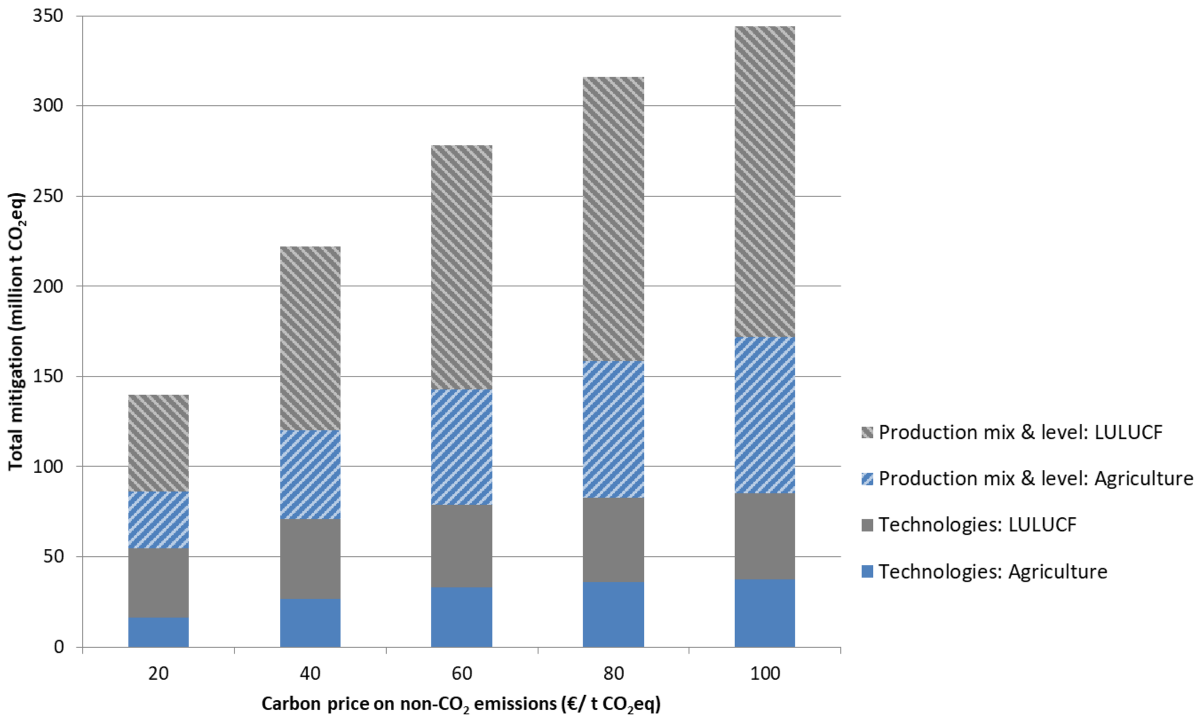
In this analysis five scenarios corresponding to five different carbon prices (CP) on agricultural non-CO_2 emissions are considered: CP 20, CP 40, CP 60, CP 80 and CP 100 Euro/t CO_2eq. The carbon prices in these scenarios imply a general incentive to mitigate non-CO_2 GHG emissions. Emissions can be mitigated by three main channels (Himics et al. 2020): *(i) technology effect ('tech only'),* mitigation directly achieved by the implementation of technological options; *(ii) production level effect,* mitigation achieved by the reduction of production levels (e.g. less cows); and *(iii) production mix effect,* mitigation achieved by changes in the composition or intensity of farming activities based on current management practices. Figure 16 shows the total mitigation achieved by the application of technological options and changes in the production mix and levels in the different carbon price scenarios at the aggregated EU-28. Four major characteristics related to technological mitigation options can be derived (Figure 16 and Table 21):

1. The contribution of mitigation technologies to total mitigation increases with increasing carbon prices but at a decreasing rate.
2. The adoption of mitigation technologies increases considerably under lower carbon prices, but further adoption is clearly limited with carbon prices beyond 60 EUR/t CO_2eq.
3. Due to the characteristics 1 and 2, the relative contribution of technology adoption to total mitigation is decreasing (from 39% in CP 20 to 25% in CP 100).
4. The relative contribution of 'agriculture' (i.e. mainly non-CO_2) emissions mitigated by technological options remains about 11% in all carbon price scenarios, whereas the relative contribution of technology-related 'LUC' emissions decreases from 28% to 14% with rising carbon prices.

Although the carbon price targets only non-CO_2 emissions from EU agriculture, on average about 65% of the total mitigation in the scenarios relates to carbon sequestration (i.e. CRF 'LULUCF') throughout all scenarios, with the LULUCF contribution from changes in production mix & level increasing from 38% to 50% with increasing carbon prices (Table 21). These LULUCF-related emission savings are secondary (i.e. side) effects resulting from the carbon price on agricultural non-CO_2 emissions.

Regarding Figure 16 it has to be reminded that the 'tech only' mitigation effects linked to the breeding measures 'milk yields' and 'ruminant feed efficiency' cannot be split from the mitigation achieved via changes in the production mix and levels.

Figure 16. Total mitigation under the combined measures approach, EU-28 (compared to the baseline, 2030)



Note: All technological mitigation options are simultaneously available in all scenarios. The 'tech only' mitigation effects linked to the breeding measures 'milk yields' and 'ruminant feed efficiency' cannot be reported in isolation and are included in the mitigation achieved by changes in the production mix and levels.

Table 21. Proportion of emissions reduction achieved via the mitigation technologies and changes in the production mix and levels, EU-28 (compared to the baseline, 2030)

	CP 20	CP 40	CP 60	CP 80	CP 100
	Share in total GHG emission reduction				
Mitigation technologies	**39%**	**32%**	**28%**	**26%**	**25%**
– Agriculture emissions	11%	12%	12%	11%	11%
– LUC emissions	28%	20%	17%	15%	14%
Change in production mix & levels *	**61%**	**68%**	**72%**	**74%**	**75%**
– Agriculture emissions	22%	22%	23%	24%	25%
– LUC emissions	38%	46%	49%	50%	50%

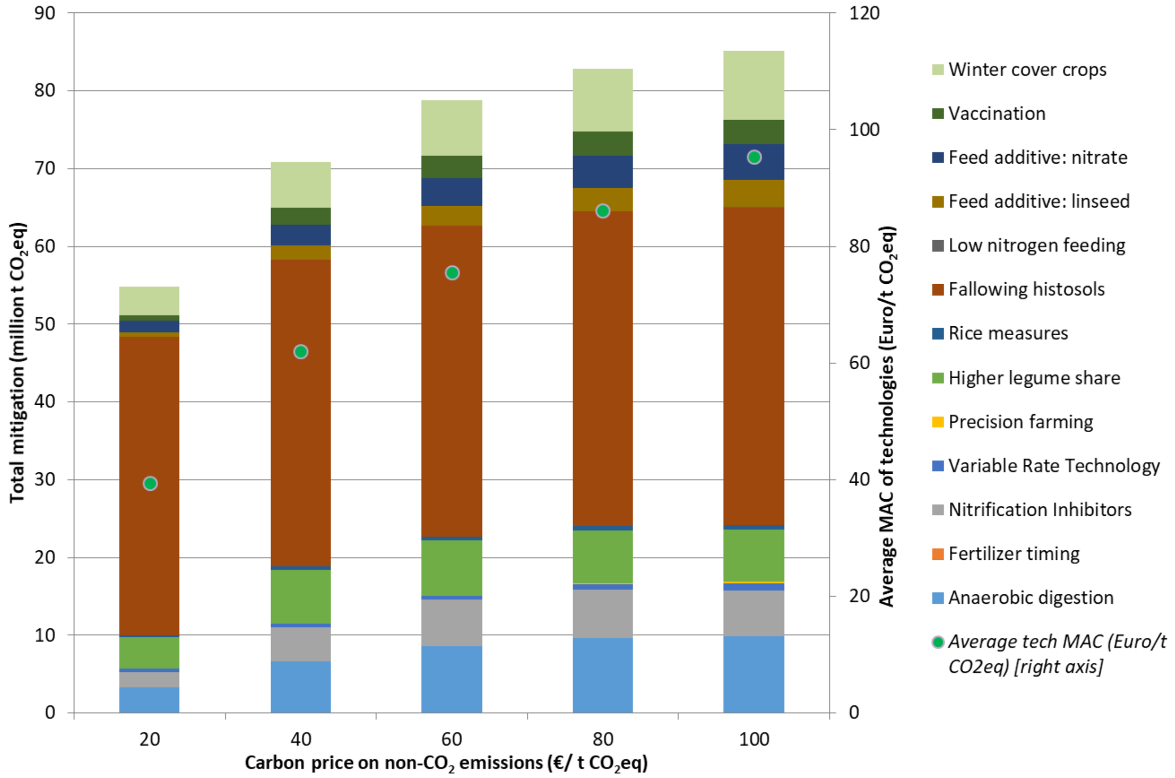
* This covers the proportion of emission reduction that cannot be directly attributed to technological mitigation options, i.e. mitigation through changes in the production mix and levels, and also the mitigation effects from the measures related to 'milk yields' and 'ruminant feed efficiency'.

While the above-mentioned four general characteristics can also be observed at MS level, the actual share of mitigation technologies in the total emissions reduction shown in Table 21 can vary considerably between MS.

For a more complete picture, the contribution of each mitigation technology to total mitigation in the carbon price scenarios is analysed in the following figures. The costs indicated on the right hand y-axis show the average MAC over all mitigation technologies in each scenario, but only considering the 'tech only' abatement. This neglects the fact that the application of some of the technologies has also direct effects on the production mix and levels (as explained in chapter 4 and shown in the 'Agriculture' and 'LULUCF' columns in Table 10 and Table 12), which render the technology more cost-effective in the context of carbon price scenarios. Neglecting these effects in the calculation of the average MAC can lead to MACs that are actually above the carbon prices in the respective scenarios.

Figure 17 shows the contribution of each technological option to total mitigation achieved under the combined measures approach at aggregated EU-28 level. By far the highest mitigation is achieved by fallowing histosols at all carbon price levels. This is followed by anaerobic digestion, higher legume share on temporary grassland, winter cover crops and nitrification inhibitors as well as the feed additives and vaccination against methanogenic bacteria in the rumen.

Figure 17. Contribution of each technology to total mitigation under the combined measures approach, EU-28 (compared to the baseline, 2030)



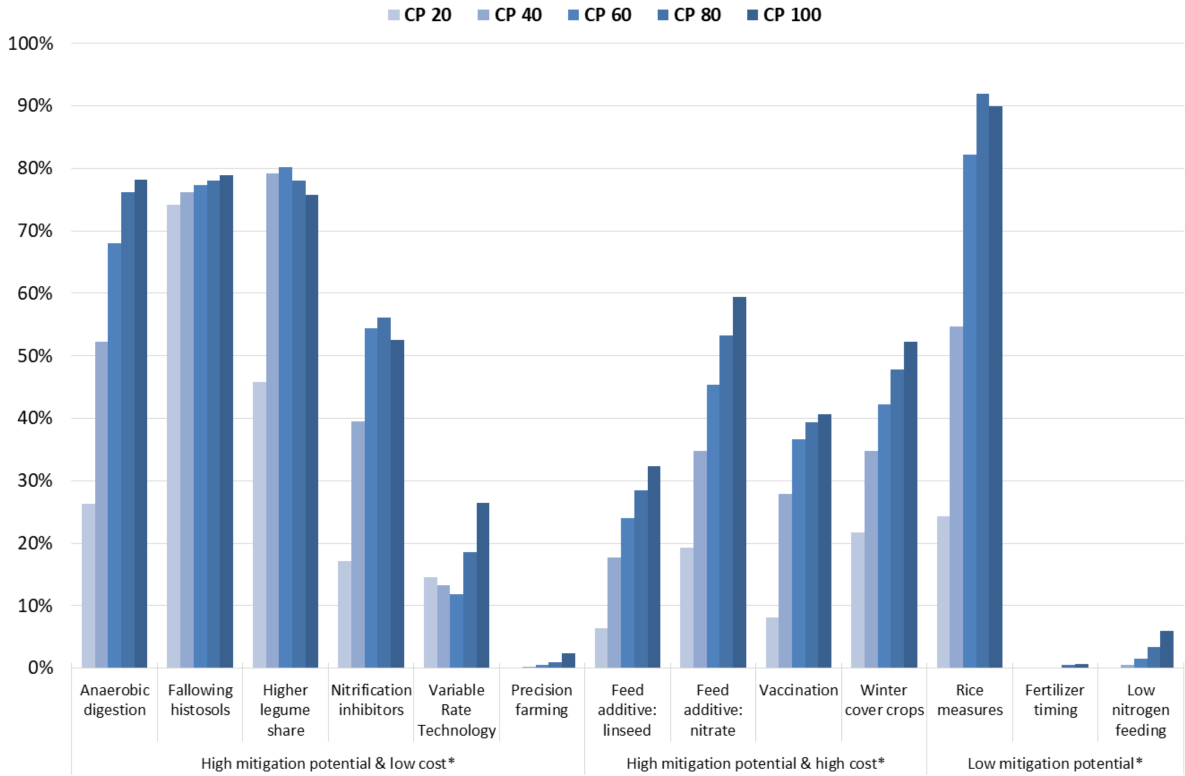
Note: All technological mitigation options are simultaneously available in all scenarios. The options 'fallowing histosols´, 'winter cover crops' and 'higher legume share on temporary grassland' also cover CO_2 emissions. The carbon price only targets agricultural non-CO_2 (methane and nitrous oxide) emitting activities.

If we compare to the standalone measures approach of section 5.2 (Figure 9), the following additional observations can be made regarding the cost-effectiveness of the technological mitigation options at EU-28 level (Figure 17):

1. Fallowing histosols, anaerobic digestion, nitrogen inhibitors, higher legume share on temporary grassland, and also rice measures contribute to mitigation already under relatively low carbon prices. This shows that they are cost-effective measures at least in some regions, and confirms their relatively low mitigation costs indicated under the standalone measures approach.
2. Winter cover crops, feed additives (linseed and nitrate) and vaccination are partially applied already at relatively low carbon prices, i.e. they are cost-effective measures in at least some regions, although they were classified as high mitigation & high cost measures (group 3) in the standalone measures approach.
3. Variable Rate Technology and precision farming are not much applied, i.e. they are less cost-effective under the combined measures approach, although both measures were classified as high mitigation & relatively low cost measures (group 1) in the standalone measures approach. This renders nitrification inhibitors as the most cost-effective option among the fertilizer-related measures under the combined measures approach.
4. Better timing of fertilizer application and low nitrogen feeding are less cost-effective measures as they are almost not applied, which confirms both their relatively high costs and generally low mitigation potential indicated under the standalone measures approach.

Looking closer at the dynamics of technology application, Figure 18 shows the mitigation achieved by each technology in the combined measures approach scenarios under different carbon prices compared to the standalone measures approach (cf. Figure 9).

Figure 18. Mitigation realised by each technology in the combined measures approach compared to the standalone measures approach, EU-28 (2030)



* Mitigation potential and costs as indicated in the standalone measures approach

The main observations regarding the dynamics of technology adoption under the combined measures approach are the following (Figure 18):

— For most of the technologies, the mitigation potential is increasingly realised with increasing carbon prices, i.e. adoption of the technology increases, but none of the technologies is applied to its maximum possible extent.

— For most of the measures, the highest increases in adoption are already realised with the introduction of carbon prices between 20 EUR and 40 EUR/t CO_2eq.

— Fallowing histosols realises about 75% of its total mitigation potential already at a carbon price of 20 EUR/t CO_2eq, and further increase is limited.

— For the fertilizer related measures, the mitigation potential of nitrification inhibitors is increasingly realised up to a carbon price of 80 EUR/t CO_2eq and then its application decreases. The application of VRT decreases between 20 and 60 EUR/t CO_2eq and increases after this again, as also precision farming is increasingly adopted with higher carbon prices (both starting to replace nitrification inhibitors). This underlines a generally higher cost-effectiveness of nitrification inhibitors at lower carbon prices compared to the other fertilizer-related measures in the combined measures approach.

— The application of higher legume share on temporary grassland decreases beyond the carbon price of 60 EUR/t CO_2eq and the adoption of the rice measures decreases beyond 80 EUR/t CO_2eq. As at the same time total rice area decreases, this implies that with the higher carbon prices it is economically better for some farmers (regions) to stop producing rice instead of applying the rice measures and continuing rice production (the same holds for the higher legume share on temporary grassland, as the total grassland area is reduced under higher carbon prices).

The general pattern of technology adoption dynamics and realisation of the mitigation potential of the technology options at the EU-28 can also be observed at the MS level. Nevertheless, as with the standalone measures approach, also in the combined measures approach some differences can be seen regarding the contribution of each technology to the total mitigation achieved at MS level.

— In France (Figure 19), fallowing histosols is confirmed as a high mitigation & low cost measure. Also, as seen for the EU-28, winter cover crops become cost-effective in several French regions. Nitrification inhibitors, higher legume shares on temporary grassland, the feed additives, vaccination and also anaerobic digestion can contribute considerably to the mitigation already under relatively low carbon prices. The general contribution of technologies to total mitigation decreases gradually from 39% to 24% under the different carbon price scenarios.

— In Germany (Figure 20) it is confirmed that fallowing histosols is especially promising. Anaerobic digestion also contributes considerably to mitigation, which shows that in several German regions anaerobic digestion is a cost-effective mitigation option already under relatively low carbon prices. Nitrification inhibitors and linseed as feed additive are also already applied under relatively low carbon prices, indicating their cost-effectiveness at least for some German regions. Overall, the contribution of technologies to total mitigation decreases from 41% to 23% under the different carbon price scenarios.

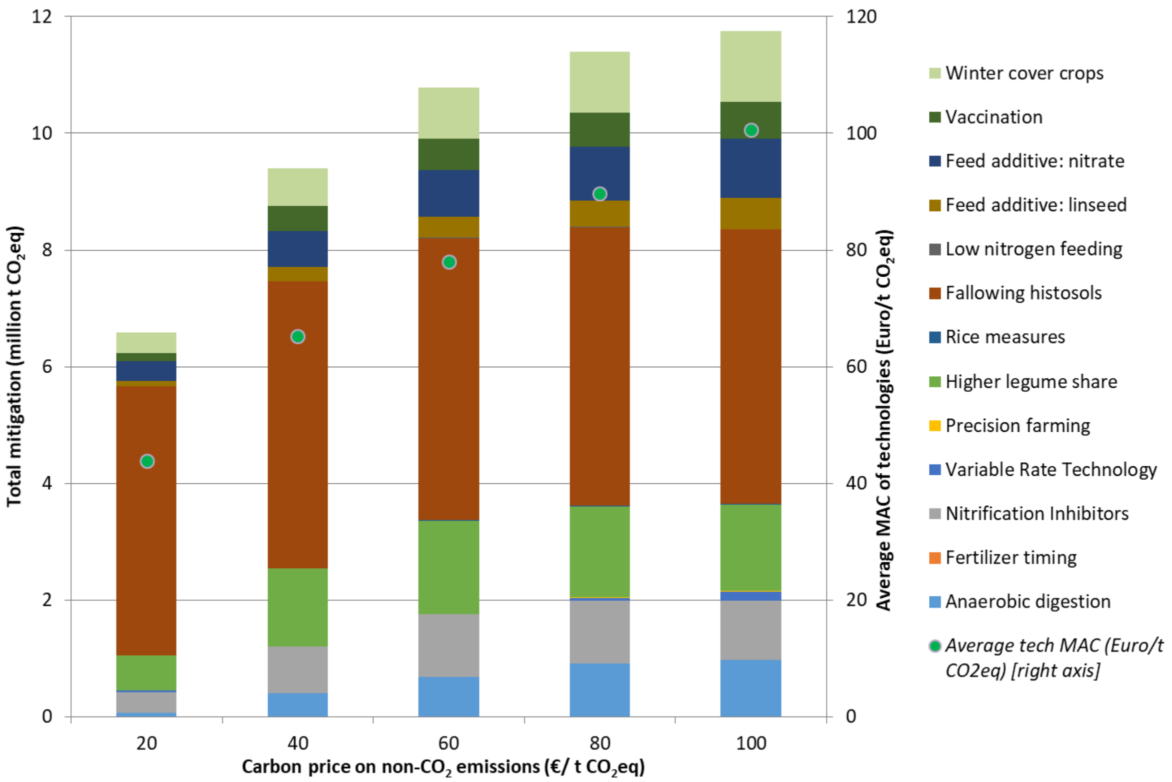
— In the UK (Figure 21), fallowing histosols and higher legume share on temporary grassland are confirmed as cost-effective measures. Winter cover crops, feed additives as well as vaccination are partly applied already under relatively low carbon prices, i.e. indicating that they are cost-effective mitigation measures for at least some UK regions. However, the general contribution from the mitigation technologies to total mitigation in the UK is rather low, decreasing from only 21% to 12% under the different carbon price scenarios.

— In Spain (Figure 22), winter cover crops, fallowing histosols, nitrification inhibitors and higher legume share on temporary grassland are confirmed to be attractive mitigation measures already at relatively low carbon prices. Anaerobic digestion is also cost-effective at least for some Spanish regions, and reaches over 80% of its total mitigation potential at a carbon price of 60 EUR/CO_2eq. The contribution of technologies to total mitigation decreases from 38% to 28% under the different carbon price scenarios.

— For Poland (Figure 23), the cost-effectiveness and high mitigation potential of fallowing histosols is confirmed. Again, nitrification inhibitors and also winter cover crops are rendered as a cost-effective measure at least for some of the Polish regions already under relatively low carbon prices. The contribution of technologies to total mitigation decreases from 55% to 39% under the different carbon price scenarios.

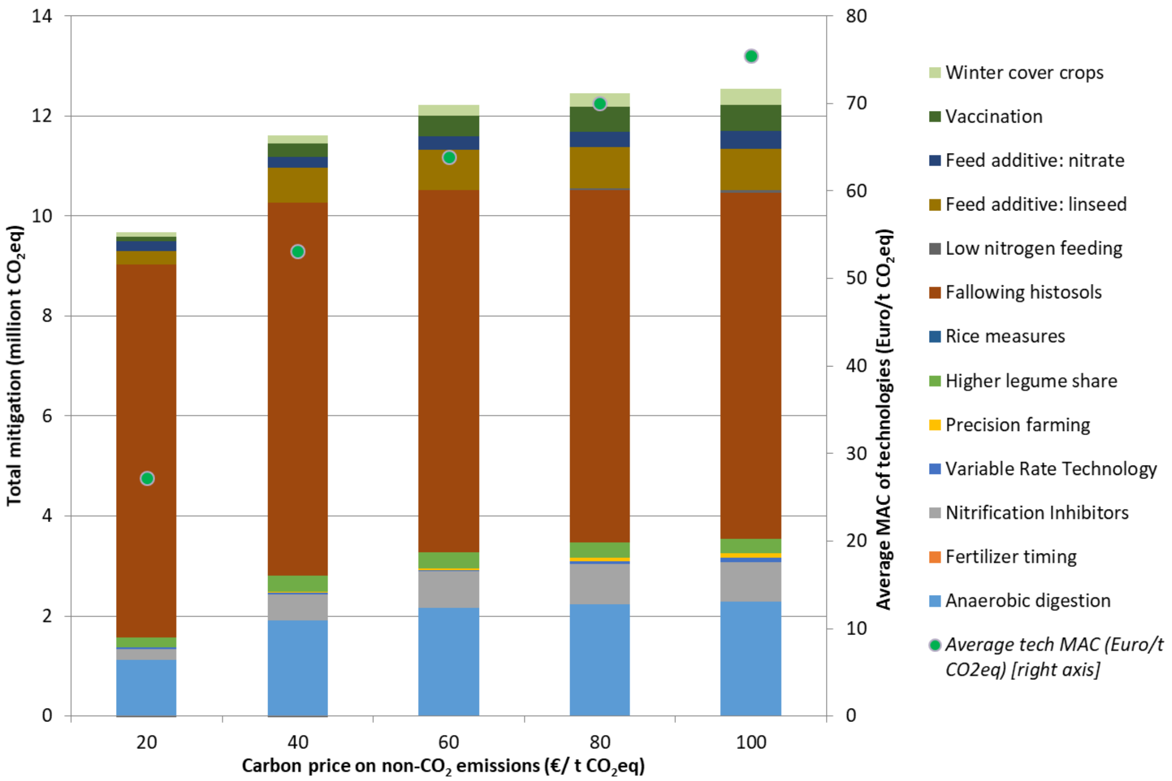
— In Ireland (Figure 24), the higher legume shares on temporary grassland, nitrification inhibitors and also fallowing histosols are confirmed as cost-effective mitigation options already under relatively low carbon prices (although the limited mitigation potential of the latter is also confirmed). Conversely, it is indicated that the feed additives, vaccination against methanogenic bacteria in the rumen, and winter cover crops could be cost-effective emission mitigation options at least for some of the Irish regions. The contribution of technologies to total mitigation decreases from 34% to 29% under the different carbon price scenarios.

Figure 19. Contribution of each technology to total mitigation under the combined measures approach, France (compared to the baseline, 2030)



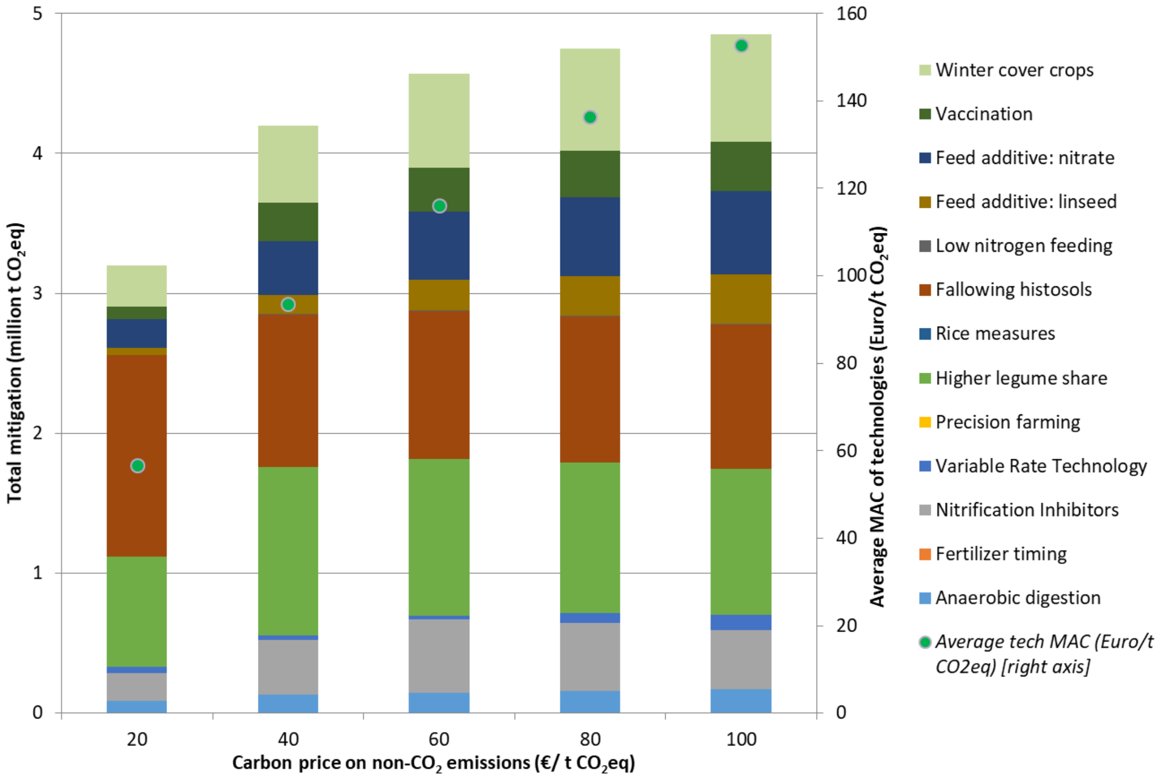
Note: All technological mitigation options are simultaneously available in all scenarios. The options 'fallowing histosols', 'winter cover crops' and 'higher legume share on temporary grassland' also cover CO_2 emissions. The carbon price only targets agricultural non-CO_2 (methane and nitrous oxide) emitting activities.

Figure 20. Contribution of each technology to total mitigation under the combined measures approach, Germany (compared to the baseline, 2030)



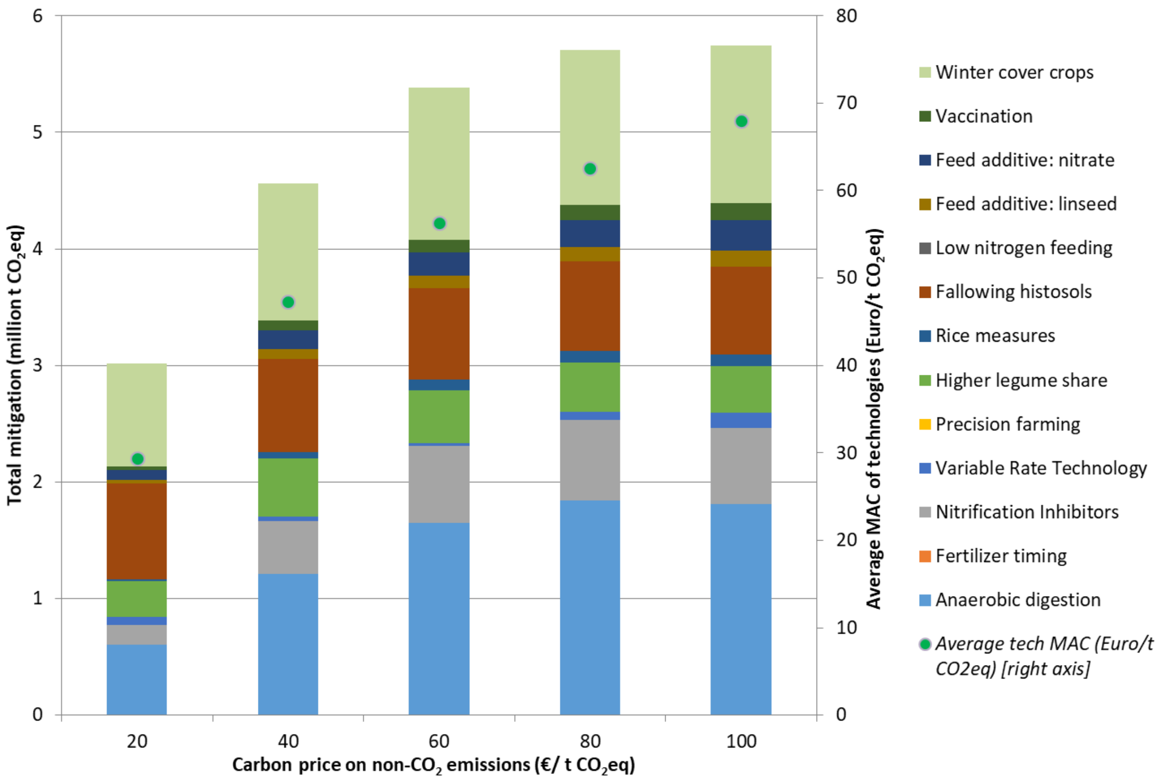
Note: All technological mitigation options are simultaneously available in all scenarios. The options 'fallowing histosols', 'winter cover crops' and 'higher legume share on temporary grassland' also cover CO_2 emissions. The carbon price only targets agricultural non-CO_2 (methane and nitrous oxide) emitting activities.

Figure 21. Contribution of each technology to total mitigation under the combined measures approach, UK (compared to the baseline, 2030)



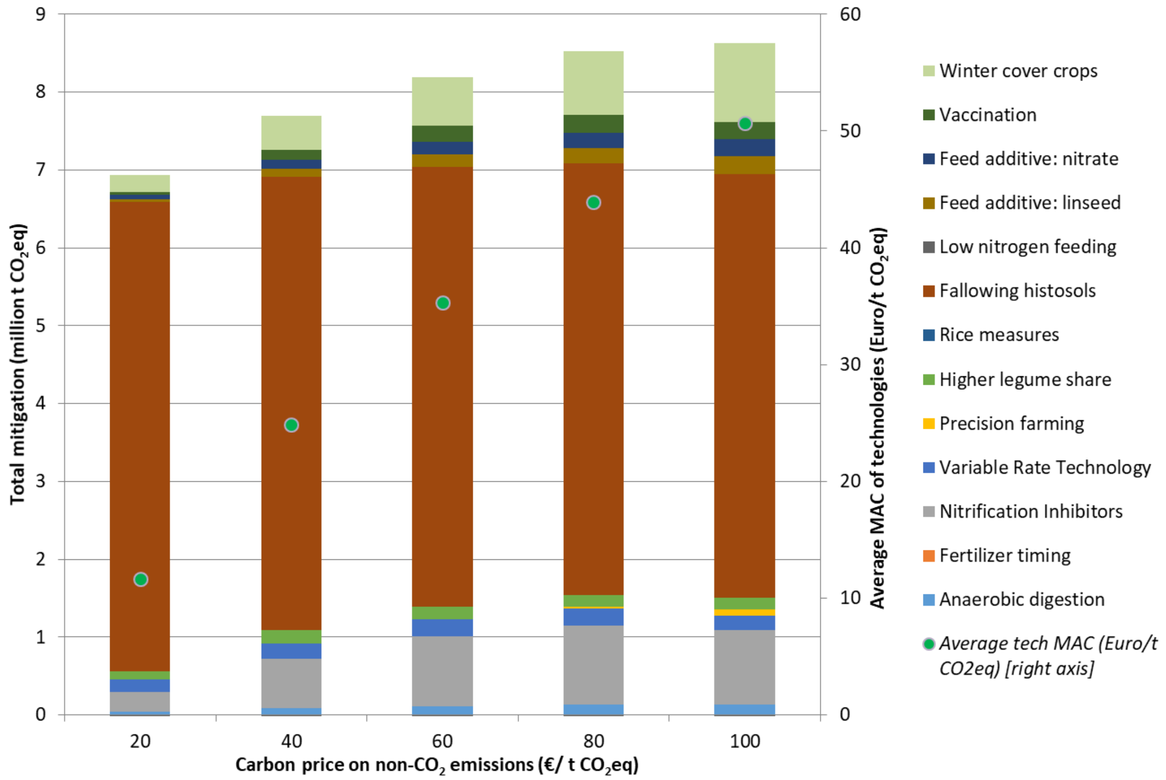
Note: All technological mitigation options are simultaneously available in all scenarios. The options 'fallowing histosols', 'winter cover crops' and 'higher legume share on temporary grassland' also cover CO_2 emissions. The carbon price only targets agricultural non-CO_2 (methane and nitrous oxide) emitting activities.

Figure 22. Contribution of each technology to total mitigation under the combined measures approach, Spain (compared to the baseline, 2030)



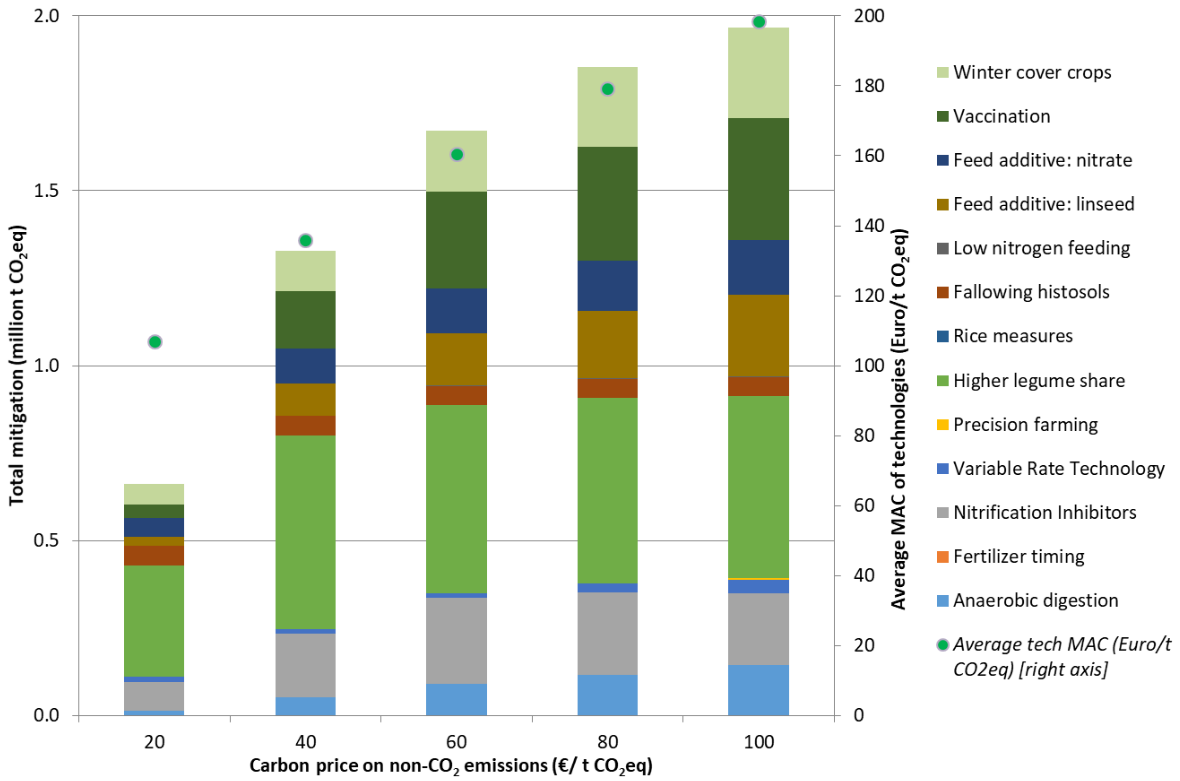
Note: All technological mitigation options are simultaneously available in all scenarios. The options 'fallowing histosols', 'winter cover crops' and 'higher legume share on temporary grassland' also cover CO_2 emissions. The carbon price only targets agricultural non-CO_2 (methane and nitrous oxide) emitting activities.

Figure 23. Contribution of each technology to total mitigation under the combined measures approach, Poland (compared to the baseline, 2030)



Note: All technological mitigation options are simultaneously available in all scenarios. The options 'fallowing histosols', 'winter cover crops' and 'higher legume share on temporary grassland' also cover CO_2 emissions. The carbon price only targets agricultural non-CO_2 (methane and nitrous oxide) emitting activities.

Figure 24. Contribution of each technology to total mitigation under the combined measures approach, Ireland (compared to the baseline, 2030)



Note: All technological mitigation options are simultaneously available in all scenarios. The options 'fallowing histosols', 'winter cover crops' and 'higher legume share on temporary grassland' also cover CO_2 emissions. The carbon price only targets agricultural non-CO_2 (methane and nitrous oxide) emitting activities.

6 Conclusions

EcAMPA 3 provides a technical framework to analyse the potential contribution of different technological mitigation options in EU agriculture to achieve GHG emissions mitigation targets. The study focuses on methodological developments for a better representation of technological mitigation options in EU agriculture with the CAPRI model, testing and analysing their mitigation potential and related costs. All technological mitigation measures have been tested in simulation runs individually and together, and MACCs specific to mitigation technologies and regions have been calculated. For the calculation of the MACCs two different approaches are followed. First, in a 'standalone measures approach' each mitigation technology is tested in isolation to assess its theoretical maximum mitigation potential and the related costs. Second, in a 'combined measures approach' all mitigation options are made available to farmers at the same time and can be adopted cumulatively. Adoption in the latter is triggered through the introduction of different carbon prices on non-CO2 emissions, taking interactions between the options into account.

The analysis highlights the importance of assessing emission mitigation from a multi-dimensional perspective. Within the boundaries of the study, we highlight the need to consider non-CO_2 and LULUCF emissions and removals for a comprehensive analysis of the sector's potential contribution to achieve GHG mitigation targets. The assessment of CO_2 emissions and removals is also important in the light of the new flexibility introduced in the EU 2030 policy framework for climate and energy.

Regarding a possible ranking of mitigation technologies, the analysis classifies them in terms of their mitigation potential and attached costs. This is valuable information towards the consideration of policy incentives for adoption of mitigation technologies within the future CAP. However, the need to consider mitigation technologies as 'a bundle' is also highlighted, avoiding the simple aggregation of mitigation potentials by individual measures without taking into account their interactions both from a biophysical and economic perspectives. Taking the theoretical maximum potential of a mitigation technology does not seem to give a clear picture on the real mitigation potential and related costs, as this does not consider the interplay with other technologies. Moreover, our spatial analysis of how mitigation measures might influence differently the agricultural sector in different MS underlines that there is no 'one fits all' rule that could be followed for the recommendation of which mitigation technologies should be implemented at regional level.

The analysis draws the following general conclusions on technological mitigation options:

— The cost-effectiveness of a mitigation technology is strongly related to the regional specificities of the farming sector, and the interplay with other mitigation options can impede or foster its adoption compared to a situation where it is considered in isolation.

— A single technology indicated as having a high mitigation potential and relatively low adoption costs at EU or MS level does not need to be representative for all regions. Conversely, mitigation options considered as having high costs at the aggregated level still can be low cost adoption measures in specific regions.

— Taking both CO_2 and non-CO_2 emissions into account renders especially fallowing of histosols as a generally cost-effective option with high mitigation potential. Higher legume share on temporary grassland and winter cover crops can also considerably contribute to mitigation, but their cost-effectiveness is very specific to the regional circumstances.

— Depending on the region, nitrification inhibitors, anaerobic digestion, rice measures, feed additives (i.e. linseed and nitrate) and vaccination of methanogenic bacteria in the rumen are indicated as cost-effective mitigation measures already under scenarios with relatively low carbon prices on non-CO_2 emissions.

— For the fertilizer-related mitigation technologies, nitrification inhibitors are indicated as more cost-effective at lower carbon prices than VRT and precision farming. Due to their generally higher unit costs, the cost-effectiveness of the latter two increases with higher carbon prices, both starting to replace nitrification inhibitors when farmers can choose among the different mitigation options.

— The scenarios with carbon prices on EU agricultural non-CO_2 emitting activities show that technological-driven mitigation somewhat levels out at carbon prices beyond 60 EUR/t CO_2eq. In other words, adoption of most of the mitigation technologies increases considerably under carbon prices below 60 EUR/t CO_2eq, but further adoption is clearly limited with higher carbon prices. Accordingly, the absolute contribution of mitigation technologies to total mitigation increases with increasing carbon prices, but at a decreasing rate. In relative terms, the contribution of mitigation technologies to total mitigation decreases from 39% under a carbon price of 20 EUR/t CO_2eq to 25% with a carbon price of 100 EUR/t CO_2eq.

— Carbon prices are set for non-CO_2 emitting activities, but on average over all carbon price scenarios about 65% of the total mitigation relates to CO_2 emissions and removals in the EU's LULUCF sector. The LULUCF contribution from technologies to total mitigation, however, decreases from 28% to 14% with increasing carbon prices, whereas the LULUCF-related contribution of changes in production level & mix increases from 38% to 50%. This underlines the general importance of taking CO_2 emissions and removals into account to get a full picture of the potential contribution of agriculture to climate change mitigation efforts.

These results have to be carefully considered within the CAPRI modelling framework and the assumptions described in this report. In order to improve the empirical basis of the modelling approach used, further research is particularly needed regarding the costs, benefits and adoption barriers of mitigation technologies (Soto et al. 2017). In addition, the following limitations are highlighted:

— In the MACCs presented, costs are fully allocated to GHG mitigation, while positive or negative side effects on other emissions, like ammonia or nitrate leaching, are ignored. Accordingly, a good ranking of a measure does not necessarily mean that this measure is cheap or favourable from a more comprehensive point of view. Conversely, the application of a measure could still be reasonable despite of a bad ranking for GHG mitigation, because it provides other benefits not considered in our MACCs.

— In the analysis carbon sequestration is considered symmetrically as negative emissions, so that the costs of one unit of removed CO_2 by carbon sequestration is treated equally as one unit of avoided emissions. However, while the reduction of emissions with a technology can be perpetuated year by year and will always provide similar annual mitigation results (compared to a situation without the technology), carbon sequestration in soils is a finite process as soils reach carbon saturation. Nevertheless, in order to avoid the loss of the sequestered carbon, farmers would have to continue applying the measure indefinitely or at least until the end of the planning horizon. For example, as soon as a farmer stops the fallowing of histosols, the carbon sequestered the years before would be released again. This effect, however, is not yet reflected in our cost data, since we consider only the costs of the years when the sequestration happens. This leads to a systematic bias in favour of measures delivering carbon sequestration compared to measures reducing emissions in the MACCs of our analysis. A solution for the future to avoid the bias might be to show MACCs for carbon sequestration and emissions separately.

For future analysis, EU MACCs for GHG mitigation in the agricultural sector should also be assessed within a market environment, taking trade and possible emission leakage effects into account. Despite these limitations, the CAPRI modelling approach is in line with the existing literature on the general determinants of technology adoption in agriculture.

From a policy context, the EcAMPA 3 study underlines that mitigation technologies can play an important role for GHG emissions reduction in the AFOLU sector, but their mitigation potential and cost-effectiveness can considerably vary at regional level. In the current policy framework (European Green Deal, Effort Sharing Regulation and CAP-post 2020), our results imply that farmers should have flexibility regarding which mitigation options to adopt, in order to find the right mix fitting to the regional circumstances. With respect to the EU's 2050 long-term strategy and how to achieve climate neutrality by 2050 (European Commission 2018), results point towards several agricultural technical and management-based mitigation options that could contribute achieving the set goals. However, the results also highlight the need for maximising the potential of technological mitigation options and the important role of innovation in agriculture to enable a cost-effective contribution of the agricultural sector to a climate-neutral EU.

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List of abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regional Impact Analysis
CH_4	Methane
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalents
CP	Carbon price (scenarios of the combined measures approach)
CRF	Common Reporting Format
DG AGRI	Directorate General 'Agriculture and Rural Development'
DG CLIMA	Directorate General 'Climate Action'
EC	European Commission
EcAMPA	Economic assessment of GHG mitigation policy options for EU agriculture
EEA	European Environment Agency
EF	Emission Factor
ESD	Effort Sharing Decision
ETS	Emission Trading System
EU	European Union
EU-15	EU including the 15 Member States before 2004
EU-28	EU including the 28 Member States before February 2020 (i.e. before Brexit)
EU-N13	EU Member States of the 2004, 2007 and 2013 enlargements
EuroCARE	European Centre for Agricultural, Regional and Environmental Policy Research
FAO	Food and Agriculture Organization of the United Nations
FM	Forest management
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies (model/database)
GDP	Gross Domestic Product
GGELS	Greenhouse Gas Emissions from Livestock Systems (EU Project)
GHG	Greenhouse Gas(es)
GWP	Global Warming Potential
IIASA	International Institute for Applied Systems Analysis
ILUC	Indirect Land Use Change
iMAP	Integrated Modelling Platform for Agro-economic Commodity and Policy Analysis
INDC	Indented Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LUC	Land Use Change
LULUCF	Land Use, Land Use Change and Forestry
MAC	Marginal Abatement Cost

MACC	Marginal Abatement Cost curve
MS	Member State(s)
Mt	Million tonnes
N	Nitrogen
N_2O	Nitrous Oxide
NO_2	Nitrite
NO_3	Nitrate
NUTS	Nomenclature of Territorial Units for Statistics
OECD	Organisation for Economic Co-operation and Development
PRIMES	PRIMES Energy System Modelling
REF	Reference scenario
TRQ	Tariff Rate Quotas
UAA	Utilised Agricultural Area
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
VRT	Variable Rate Technology
WTO	World Trade Organization

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Annex. Restriction of fertiliser measures

The reduction effects of fertiliser technologies in EcAMPA are based on information from the GAINS database (2015)[29]. However, based on information from fertiliser sales, animal production, crude protein content of plants, yields, etc., CAPRI estimates endogenous 'business-as-usual' over-fertilisation factors (i.e. nitrogen availability divided by nitrogen need) at the regional level. Thus, by simply applying the reduction factors of mitigation technologies from GAINS, we could end up with an availability of nitrogen below the actual plant need.

To avoid this, an upper limit for the reduction effect of all measures is applied. This upper limit corresponds to the 'business-as-usual' over-fertilisation factor plus 10 %. However, by applying only the upper limit, cheaper fertiliser reduction measures could be selected, which could pose a problem, as a low over-fertilisation factor indicates an already efficient fertilisation strategy, implying that further reduction might be possible only with more sophisticated, usually more expensive, technologies. Therefore, cheaper technologies are increasingly restricted for lower over-fertilisation factors.

We start from the assumption that, with a 100 % application share of precision farming (i.e. the most efficient technology), we cannot achieve more reduction than the business-as-usual over-fertilisation plus 10 % or, in other words, we cannot go below the nitrogen need minus 10 %. For regions where the level of nitrogen fertilisation with the full application of precision farming remains above this value (i.e. nitrogen need minus 10 %), we do not need to change anything. In contrast, if it is below, we reduce the maximum implementation share for all mitigation technologies. The basic idea is that we have to reduce the potential of all measures by the difference between the theoretical reduction potential of precision farming and the actual reduction potential defined based on the nitrogen need.

Following this method, we assume that, on average, a farmer will first apply cheap measures and then the more expensive ones. If the potential of precision farming is lower than in theory, this is because equivalent measures to the cheap technologies have already been implemented (e.g. VRT) and are, therefore, no longer available. Therefore, we redefine the maximum implementation share of a technology, *msh(tech)* (i.e. the maximum proportion of the total nitrogen from mineral fertilisers in the region to which the technology is applicable), in the following way:

$$\mathrm{msh}'(tech) = \frac{n(noc) - min[n(noc), (n(tech) + n(need) * 0.9 - n(pf))]}{n(noc) - n(tech)}$$

where *n*(*noc*) is the fertiliser application in the reference scenario (business as usual); *n*(*tech*) is the fertiliser application with the technology, *tech*, according to information from GAINS; *n*(*need*) is the fertiliser need; and *n*(*pf*) is the fertiliser application when precision farming is applied.

Assuming that *n*(*noc*) = 140 tonnes, *n*(*pf*) = 100 tonnes, *n*(*need*) = 120 tonnes and *n*(*tech*) = 135 tonnes, we would add the difference between *n*(*need*) * 0.9 and *n*(*pf*) (108 – 100 = 8 tonnes) to *n*(*tech*), which gives 143. As 143 is higher than *n*(*noc*), we reduce this to the maximum value of *n*(*noc*) (140 tonnes). In total, we get a maximum implementation share, *msh'*(*tech*), of zero ((140 – 140)/(140 – 135) = 0), because we assume that the relatively small reduction potential of the technology has already been achieved via other equivalent measures. By contrast, assuming that *n*(*tech*) = 115 tonnes, we end up with a value of 123 tonnes and, as a consequence, with a maximum implementation share, *msh'*(*tech*), of 17/25. So, only 8/25 of the potential has already been achieved in the baseline via equivalent measures. Obviously, precision farming would end up with a maximum implementation rate of 80 %, which guarantees that the value of *n*(*pf*) will be equivalent to *n*(*need*) * 0.9.

([29]) This explanation of the restriction of reduction the mitigation potential of the fertiliser measures is taken from Annex 2 of the EcAMPA 2 report (Pérez Domínguez et al. 2016).

KJ-NA-30164-EN-N

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of the European Union

doi:10.2760/4668

ISBN 978-92-76-17854-5