Methane emissions from enteric fermentation in CAPRI

A Technical Documentation on accounting, modelling and reporting

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1 INTRODUCTION

1.1 Definition of the problem

CAPRI is a large partial equilibrium model of the agricultural sector with a focus on the European Union. It is used by a large community of researchers and policy makers and it is in constant maintenance and development by a network of researchers. Keeping track of the developments and documenting them is a key task, since documentation facilitates model use and the analysis and interpretation of results. However, documentation is often not included as an integral part of the different development or research projects. Also, to track the developments of different researchers related to one topic is a process which requires time since the network of developers is international with researchers with different research agendas. In consequence, the documentations available (like Britz, Witzke 2014) might be incomplete or not up to date.

This paper circumvents the challenge of a full update of Britz, Witzke 2014 by a selective focus: documenting how the methane emissions from enteric fermentation are calculated in CAPRI. In exchange for a narrow focus this documentation tries to cover also the technical modeling details including the presentation of equations as well as insights on GAMS code used and their location in the file structure of the model. Subsequent experience and feed-back from users will show whether this format is a promising prototype for follow up efforts on other topics.

The paper documents how the methane emissions from enteric fermentation are currently modeled (as of April 2018). However, please note that it heavily draw upon two previous documentations with internal dissemination only[1]. Their text and examples, if used, have been reviewed and updated.

1.2 Definition of methane emissions from enteric fermentation and IPCC recommendation on how to calculate them

Enteric fermentation is a digestive process which produces methane as a by-product. The rate of methane emissions depends, in the first line, on the type of the digestive system and is much higher in the case of ruminant livestock (e.g. cattle, sheep, goats, buffalo and camels) than in the case of Non-ruminant herbivores (horses, mules, asses) or monogastric livestock (swine). Therefore, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories recommend a more precise approach for the calculation of emissions (Tier 2 or Tier 3) of the ruminant species which play a major role in a

[1] The documentations used as a based are. (i) Weiss, F., "The calculation of Greenhouse Gases in CAPRI" and (ii) Witzke, P. (2016), "CAPRI GHG emission accounting and EcAMPA-II", Deliverable D2 of the specific contract No. 154208.X10: "Update of technological mitigation options: Documentation".

country. For all other species, a simplified approach (Tier 1) is considered to be sufficient. The Tier 1 method uses default emission factors which are directly applied to the annual average livestock population. In contrast, the Tier 2 method requires the calculation of regional emission factors, which are derived from different regional gross energy intake values which depend on different production conditions (e.g. stall or pasture production systems, or different diets with different digestibility factors).

1.3 How are the emissions considered in CAPRI

In CAPRI, the methane emissions from enteric fermentation (CH4ENT) are currently considered in an endogenous way, in the sense that

(i) the gross energy intake is calculated endogenously: for this the feed intake endogenously calculated in CAPRI is used (which includes different feed types) and,

(ii) the share of application of mitigation measures addressing the CH4ENT emissions, as well as the share of application of other mitigation measures addressing other GHG gases, are calculated endogenously.

However, the calculation of GHG emission in CAPRI has been, and it will remain like this, a process that is continuously being improved. Before the gross energy intake and the shares of the mitigation functions were endogenized, the CH4ENT emissions were calculated based on gross energy intakes computed on the basis of animal categories, animal weights, milk and meat yields, energy requirements during pregnancy, etcetera. These calculations are still active in CAPRI and can be used for comparison and evaluation of the results with the endogenous features already mentioned. Also, the values on gross energy consumption from the old approach still enter the calculation of methane emissions from manure management (CH4MAN).

1.4 Structure of the documentation

In this document both calculation approaches, the old one (used in the period of time previous to 2014) and the new one (used from 2014 on) are described and explained in Section 2 and Section 3. Section 4 gives examples of the application and the consequences of the mitigation measures addressing CH4ENT that are currently considered endogenously in CAPRI.

1.5 Background information on CAPRI's accounting system

There is some background information needed to understand the CAPRI emission accounting. This is the distinction between "herd size" and "activity level" in the animal sector. The former gives the stock of animals of some category observed at some counting day or as an average over several counting days (stable places). For fattening activities, the latter (the activity level) is the number of animals produced during one year (a flow concept). If we assume for simplicity that fattening of pigs takes 0.5 years then the activity level (number of slaughtered pigs) would be twice the herd size observed at some counting day. In general we may transform between herd size ($herd$) and the activity levels ($actLevl$, in 1000 heads/year) using the production days (ProdDays) of each animal activity (the elements of the set *MAACT*):

Equation 1. Transformation from herd size to activity levels

$$actLevl_{MAACT} = herd_{MAACT} * \frac{365}{ProdDays_{MAACT}}$$

The variable *ProdDays* gives the process length of the corresponding production process and animal activity. These often differ from 365 days and are defined in CAPRI as follows:

- *ProdDays* = "fattening days"[2] for bulls for fattening (BULF, typical value: 270 days), calves for fattening (CALF, typical value: 170 days), calves for raising (CALR, typical value: 350 days), heifers for fattening (HEIF, typical value: 310 days), heifers for raising (HEIR, typical value: 630 days) and sheep and goats for fattening (SHGF, typical value: 220 days). For single countries, the fattening days computed from Eq 1 may differ substantially from typical values, depending on the statistical data for slaughterings per year (~ activity level) and survey data on herd size.
- *ProdDays* = "365" (= whole year) for dairy cows (DCOW), suckler cow (SCOW), sheep and goats for milk (SHGM) (as well as sows and hens, which are irrelevant though for enteric fermentation).

In CAPRI the energy requirements and the emission factors are computed per unit of the respective activity level, which is per single animal (per head) and associated process length (i.e. using the example from above: for one pig in 6 months). In this documentation, this denominator of certain coefficients (requirements, emissions) is indicated to be (i) "per unit of activity level" or (ii) simply "per unit of level". Then, by multiplying the emission factor with the corresponding activity level

2 For raising activities like HEIR, CAMR, CAFR it would be less confusing to call them "raising days" but they are stored on the same parameter in req_or_man_fct.gms (p_fatnDays).

(actLevl) (i.e. using the example from above: the total slaughtered pigs in one year) one gets the total GHG emissions for an animal activity in one year. This is exactly the same relationship that holds for output coefficients like crop yields or slaughter weights or for input coefficients like "other input use per unit of level" (ha or head with some process length), see Section 3.1 of Britz, Witzke 2014.

2 PRE-2014 TIER 2 APPROACH FOR DAIRY COWS AND OTHER CATTLE

The calculation of Tier 2 emission factors is based on the approach suggested by the 2006 IPCC Guidelines (Volume 4, Chapter 10). Therefore, in a first step, net energy requirements (per unit of activity level) for maintenance, daily activity, growth, lactation and pregnancy are calculated. In a second step, gross energy intake and emission factors (per unit of activity level) are derived from the energy requirements and digestibility factors.

2.1 Step 1: Calculation of net energy requirements

2.1.1 Net energy for maintenance (NE_m)

NE_m is the energy required to maintain the animal in equilibrium where no body energy is gained nor lost (Jurgen, 1988 cited by IPCC, 2006).

Equation 2. Net energy for maintenance as used in CAPRI (dairy cows and other cattle)

$$NE_m = Cf_i * (BW)^{0.75} * ProdDays$$

Source: IPCC (2006) Vol. 4, Ch.10, Equation 10.3 with adaptations
Location in CAPRI file structure: …\gams\feed\req_or_man_fnc.gms

Where:	CAPRI code or value:
NE_m = net energy for maintenance, MJ per unit of activity level (i.e. per head and process length). The production process may be fattening, raising or keeping of animals	p_animReq(RS,**,A,"NEM")
Cf_i = a coefficient which varies for each animal category as shown in Table 10.4 from IPCC 2006 Guidelines, MJ day^{-1} kg^{-1}	0.386 (dairy and suckling cows) 0.322 (calves and heifers) 0.37 (young bulls)
BW = average live weight of animal, kg	p_meanLiveWgt
$ProdDays$ = fattening days, raising days or year as explained in Section 1.5.	p_fatngDays or p_animProdDays

** The parameter is defined for the following set elements (at the same time, the elements might also be sets, in that case its elements are stated in parenthesis): DCOW (DCOL and DCOH), SCOW, CALF (CAMF and CAFF), CALR, BULF (BULL and BULH), HEIF (HEIL and HEIH), HEIR.

For the average live weight (BW), 600 kg are assumed for dairy cows, 550 kg for suckling cows, and 425-450 kg (depending on the relative herd size of dairy and suckling cows) for heifers for rearing. For the fattening categories the average live weight is calculated for different fattening periods by using the mean of the starting and the end weight in the considered fattening period.

2.1.2 Net energy for activity ($\boldsymbol{NE_a}$)

NE_a is the energy need by the animals to obtain their food and it is based on their feeding situations as i.e. “stall” or “pasture” or “grazing large areas” (IPCC, 2006).

Equation 3. Net energy for activity as used in CAPRI (dairy cows and other cattle)

$$NE_a = C_a * Cf_i * (BW)^{0.75} * PastureDays$$

Source: IPCC (2006) Vol. 4, Ch.10, Equation 10.4 with adaptations
Location in CAPRI file structure: …\gams\feed\req_or_man_fnc.gms

Where:	CAPRI code or value:
NE_a = net energy for activity, MJ per unit of activity level (i.e. per head and process length)	p_animReq(RS,**,A,"NEA")
$Cf_i * (BW)^{0.75}$ = net energy for maintenance	
C_a = coefficient corresponding to the animal’s feeding situation according to table 10.5 from IPCC 2006 Guidelines	0.00 (Stable) 0.17 (Pasture)
$PastureDays$ = days spent on pasture	(365-p_rcEmissions(RS,**,"HD")*(1-p_rcEmissions(RS,**,”ET”): where “HD” is housing days and “ET” the extra time for milking spent in stable during the grazing period

** The parameter is defined for the following set elements: DCOW (DCOL and DCOH), SCOW, CALF (CAMF and CAFF), CALR, BULF (BULL and BULH), HEIF (HEIL and HEIH), HEIR.

Note: in CAPRI it is assumed for simplicity that any grazing occurs in Europe under conditions of pasture (modest energy expense to acquire feed), ignoring the IPCC category of “grazing large areas” (high energy requirement from IPCC table 10.5). Note also that under stable conditions $C_a = 0$. Equation 3 uses the time of animals on pasture (*PastureDays*) as a factor. They are taken from the MITERRA model (which in turn has relied on the IIASA-RAINS database) and *PastureDays* changes depending on the animal category and the country.

2.1.3 Net energy for lactation (NE_l)

NE_l is the energy needed for lactation. It is a function of the amount of milk produced and its fat content (IPCC 2006 Guidelines).

Equation 4. Net energy for lactation (used for dairy and suckler cows in CAPRI)

$$NE_l = (1.47 + 0.40 * FAT) * MilkPerDay * LactDaysPerYear$$

Source: IPCC (2006) Vol. 4, Ch.10, Equation 10.8 with adapations
Location in CAPRI file structure: …\gams\feed\req_or_man_fnc.gms

Where:	CAPRI code or value:
NE_l = net energy for lactation, MJ per unit of activity level (i.e. per head and process length). In this case the process length is the *LactationDaysPerYear*, since milk producing animals live longer than a year.	p_animReq(RS,**,A,"NEL")
FAT = Fat content of milk, % by weight	p_milkFatCont(RS,"FATS")
$MilkPerDay$ = amount of milk produced, kg of milk per day	p_milkPerDay(RS,**,%yr_A%)
$LactDaysPerYear$ = the number of days of lactation in a year	305 (dairy cows) 125 (suckler cows)

** The parameter is defined for the following set elements: DCOW (DCOL and DCOH), SCOW.

The total milk production per head comes from the CAPREG database and is divided by an assumed lactation period of 305 days in order to get the daily milk production. For the fat content a default value of 4% is assumed.

2.1.4 Net energy for pregnancy (NE_p)

NE_p is the energy required for the gestation period (281 days for cattle and buffalo). This energy averaged over the entire year is calculated to be 10% of NE_m.for cattle and buffalo (IPCC 2006 Guidelines).

Equation 5. Net energy for pregnancy (used for dairy and sucker cows in CAPRI)

$$NE_p = NE_m * C_{pregnancy} * 365$$

Source: IPCC (2006) Vol. 4, Ch.10, Equation 10.13
Location in CAPRI file structure: …\gams\feed\req_or_man_fnc.gms

Where:	CAPRI code or value:
NE_p = net energy for pregnancy, MJ per unit of activity level (i.e. per head and process length). In this case the process length is a year since NEp is calculated only for DCOW and SCOW.	p_animReq(RS,**,A,"NEP")
$C_{pregnancy}$ = pregnancy coefficient	0.10

** The parameter is defined for the following set elements: DCOW (DCOL and DCOH), SCOW.

2.1.5 Net energy for growth ($\boldsymbol{NE_g}$)

NE_g is the net energy needed for weight gain (IPCC 2006 Guidelines).

Equation 6. Net energy for growth as used in CAPRI

$$NE_g = 22.02 * \left(\frac{BW}{C * MW}\right)^{0.75} * WG^{1.097} * ProdDays$$

Source: IPCC (2006) Vol. 4, Ch.10, Equation 10.6

Location in CAPRI file structure: …\gams\feed\req_or_man_fnc.gms

Where:	CAPRI code or value:
NE_g = net energy for growth, MJ per unit of activity level (i.e. per head and process length)	p_animReq(RS,…,A,"NEG")
BW = the average live body weight (BW) of the animals in the population, kg	p_meanLiveWgt(RS,*[1],%yr_A%)
C = a coefficient with a value of 0.8 for females, 1.0 for castrates and 1.2 for bulls (IPCC 2006 Guidelines)	p_coeffEnergyForGrowth(*[1]): Calves masculine: 1.0 Calves feminine: 0.8 Bulls: 1.2 Heifers: 0.8 source: feed_decl.gms (line 209)
MW = the average mature live body weight of an adult female in moderate body condition, kg	p_femWgt(RS,A)
WG = the average daily weight gain of the animals in the population, kg per day	p_dailyWgtIncrease(RS,*[1],%yr_A%)
$ProdDays$ = fattening days, raising days or year as explained in Section 1.5	p_fatngDays or p_animProdDays*[2]

Note 1: The parameter is defined for the following set elements: CALF which contains the elements CAMF and CAFF, CALR, HEIF (HEIL, HEIH), HEIR and BULF (BULL, BULH).

Note 2: usually the two parameters p_fatngDays and p_animProdDays are equal and correspond to "ProdDays". However for some processes like fattening of heavy calves the process is split into two phases to increase the accuracy. And in these cases p_fatngDays denotes the length of the respective phase whereas p_animProdDays denotes the whole process length.

The net energy required for the weight gain depends on the daily weight increase (*WG*) and the live body weight of the animal in the population (*BW*). The mature live body weight of an adult female in moderate body condition (*MW*) is a weighted average of the weight of suckling cows and dairy cows, while the daily weight gain (*WG*) depends on the age of the animals. For example, in the case of calves for fattening it ranges between 0.8 and 1.2 kg/day, while calves for rearing gain 0.6 kg/day up to a weight of 150 kg and between 0.8 and 1.1 kg/day from 151 kg to 335 kg (males) and 300 kg (females). For young bulls daily weight gain ranges from 0.8 to 1.5 kg/day. Heifers for fattening are assumed to gain between 0.6 and 1.0 kg/day.

2.2 Step 2: Gross energy intake and emission factors

Once the net energy requirements for the different animal conditions (maintenance, activity, lactation, pregnancy and growth) are calculated, the gross energy intake (GE) and the corresponding emission factors (EF) are computed.

Note that prior to the GE and EF calculations, the net energy requirements from Section 2.1 are transformed from "per unit of activity level (i.e. per head and process length)" to a daily basis. This occurs at the end of the req_or_man_fnc.gms file (Figure 1).

Figure 1. GAMS code for the transformation of the unit of the net energy requirements from "per unit of actLevl (i.e. per head and process length)" into "per head and day"

```
*
* --- change definition from per year to per day (to ease interpretation)
*
  p_animReq(RS,AACT,A,REQSR)  $ p_animProdDays(RS,AACT,%yr_A%) = p_animReq(RS,AACT,A,REQSR)/p_animProdDays(RS,AACT,%yr_A%);
  p_animReq(RS,AACT,A,SUBENE) $ p_animProdDays(RS,AACT,%yr_A%) = p_animReq(RS,AACT,A,SUBENE)/p_animProdDays(RS,AACT,%yr_A%);
```

Location in CAPRI file structure: …\gams\feed\req_or_man_fnc.gms

2.2.1 The gross energy intake ($\boldsymbol{GE}$)

The GE requirement is derived based on the sum of the net energy requirements and the digestibility characteristics of the feeds as expressed in the REM and REG (the *R*atio of net *E*nergy available in a diet for *M*aintenance to digestible energy and the *R*atio of net *E*nergy available in a diet for *G*rowth to digestible energy).

Equation 7. Gross energy as used in CAPRI (cattle and sheep activities)

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_p}{REM} \right) + \left(\frac{NE_g}{REG} \right)}{\frac{DE\%}{100}} \right]$$

Source: IPCC (2006) Vol. 4, Ch.10, Equation 10.16
Location in CAPRI file structure: …\gams\envind\gases.gms

Where:	CAPRI code or value:
GE = Gross energy, MJ per unit of activity level and day	p_animReq(RU,MAACT,A,"GENE")
NE_m = net energy for maintenance, MJ per unit of activity level and day	See Equation 2
NE_a = net energy for activity, MJ per unit of activity level and day	See Equation 3
NE_l = net energy for lactation, MJ per unit of activity level and day	See Equation 4
NE_p = net energy for pregnancy, MJ per unit of activity level and day	See Equation 5
NE_g = net energy for growth, MJ per unit of activity level and day	See Equation 6
REM = ratio of net energy available in a diet for maintenance to digestible energy consumed	EMISCALC(RU,MAACT,A,"GENE")
REG = ratio of net energy available for growth in a diet to digestible energy consumed	EMISCALC(RU,MAACT,A,"NEG")
$DE\%$ = ratio of digestible energy in a diet to gross energy consumed (i.e. 80% digestibility is expressed in the equation as 80; thus, after computing $DE\%/100$ one would get 0.8)	EMISCALC(RU,MAACT,A,"DE")

2.2.2 The emission factor ($\boldsymbol{EF}$)

The emission factors for each category of livestock are estimated based on the gross energy intake and the methane conversion factor (Y_m) for the category (IPCC 2006 Guidelines). Y_m gives the extent to which feed energy is converted to CH_4 and it depends on the animal category, feed characteristics and production practices. For cattle and buffalo, the IPCC 2006 Guidelines give a general estimate of $6.5\% \pm 1.0\%$ and it suggest to use lower and upper bounds in the cases of good and bad quality feed respectively.

Equation 8. CH4 emission factor for enteric fermentation

$$EF = \left[\frac{GE * Y_m * ProdDays}{55.65}\right]$$

Source: IPCC (2006) Vol. 4, Ch.10, Equation 10.21 with adaptations
Location in CAPRI file structure: …\gams\envind\gases.gms

Where:	CAPRI code or value:
EF = Emission factor, kg CH4 per unit of activity level (i.e. per head and process length)	EMISCALC(RU,MAACT,A,"CH4ENT")

GE = Gross energy, MJ per unit of activity level and day	p_animReq(RU,MAACT,A,"GENE")
Y_m = methane conversion factor, percentage of GE in feed converted to methane	EMISCALC(RU,MAACT,A,"YM")
$ProdDays$ = fattening days, raising days or year as explained in Section 1.5	p_fatngDays or p_animProdDays
The factor 55.65 (MJ/kg CH4) is the energy content of methane	

The resulting country specific emission factors for dairy cows, non-dairy cattle and sheep and goat in the EU28 and for the year 2012 are presented in Table 1. As a reference, the emissions factors used in the national inventories are also given.

Table 1. Emission factors from enteric fermentation for dairy cows, non-dairy cattle and sheep and goat in 2012 (kg CH4 per head and year)

	Dairy Cows		Suckling cows	Male adults for fattening	Heifers for fattening	Heifers for raising	Male calves for fattening	Female calves for fattening	Male calves for raising	Female calves for raising	Non Dairy		Sheep and Goat	
EU	CAPRI	NI[1]	CAPRI	CAPRI	CAPRI	CAPRI	CAPRI	CAPRI	CAPRI	CAPRI	CAPRI	NI[1]	CAPRI	NI[1]
Austria	133	129	88	143	168	56	26	29	38	33	57	60	8.0	7.5
Belgium Luxemburg	129	138	78	131	139	49	37	40	31	29	52	51	8.0	15.9
Bulgaria	130	109	102	142	138	78	31	33	29	33	54	45	8.0	6.5
Croatia	104	109	70	140	121	40	30	30	33	30	41	49	8.0	7.4
Cyprus	125	116	79	101	91	39	26	27	24	23	31	57	8.0	6.7
Czech Republic	167	137	69	173	140	59	40	42	31	34	55	55	8.0	7.7
Denmark	170	146	86	156	142	58	38	39	39	37	52	38	8.0	7.6
Estonia	246	136	126	206	192	72	35	12	54	51	70	45	8.0	7.8
Finland	177	145	98	166	147	61	29	30	40	38	59	53	8.0	8.3
France	155	120	89	121	138	59	29	27	35	26	57	51	8.0	9.5
Germany	149	135	70	151	138	51	25	29	34	32	49	44	7.6	6.1
Greece	139	121	89	111	115	43	25	27	26	24	54	61	8.0	7.8
Hungary	150	130	92	131	144	60	28	33	29	29	53	54	8.0	7.8
Ireland	152	111	95	156	142	55	30	35	38	36	64	47	8.0	5.7
Italy	131	135	88	129	125	51	26	34	27	26	48	48	8.0	7.7
Latvia	168	131	117	184	161	66	35	43	40	39	99	40	8.7	7.6
Lithuania	193	119	135	220	198	93	64	65	54	51	46	53	7.3	10.8
Malta	126	124	45	99	97	39	22	23	25	23	34	31	8.0	11.4
Netherlands	150	128	85	125	145	57	27	33	33	30	40	37	8.0	7.2
Norway	163	142	99	173	142	72	24	28	39	38	61	61	8.0	14.2
Poland	118	116	86	110	105	53	18	19	30	28	44	50	8.0	7.2
Portugal	163	131	89	129	106	49	24	30	26	23	55	62	8.0	8.9
Romania	100	97	57	121	123	56	30	34	29	31	43	64	8.0	18.3
Slovakia	170	110	113	211	191	89	46	33	47	46	75	54	8.0	9.4
Slovenia	118	121	72	121	113	44	23	22	25	24	45	55	8.0	7.3
Spain	149	103	75	123	125	51	28	31	24	22	51	42	8.0	7.5
Sweden	186	130	104	170	149	62	43	49	43	41	65	55	8.0	8.0
United Kingdom	180	126	93	167	138	55	21	41	37	36	62	65	8.0	5.1

Sources: UNFCCC submission 2016 for year 2012 (retrieved in May 2018 from https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2018); CAPRI output from module "CAPREG base year" for base year = 2012. CAPRI results shown in this document were produced with code from r7038 of https://svn1.agp.uni-bonn.de/svn/capri/trunk and based on baseline results from r11 of https://svn1.agp.uni-bonn.de/svn/capri_out_after2016/results.

[1] NI denotes "National Inventories"

2.3 Step 3: Total CH4ENT emissions from dairy cows and other cattle

The final step is the calculation of the total CH4ENT. This is done with the following:

Equation 9. Calculation of total CH4ENT from each activity

$$(methane\ emissions\ per\ unit\ of\ activity\ level) * (the\ activity\ levels)$$

Example: HEIR.CH4ENT*HEIR.LEVL is the product of methane from enteric fermentation per heifer raised times the number of heifers raised in a year. Note that there is no specific table in the graphical user interface (GUI) with the name “total emissions per emission type”. For this one must select the table “Environmental indicators per activity, multiplied with activity levels”. This gives the above contributions from each activity as well as their aggregates, for example to “total beef cattle”. As the sum of all agricultural activities is also one of the aggregates (code AGGT), the table also gives total agricultural emissions together with a detailed breakdown of to the contributions from each activity.

3 Post 2014 approach

In the new approach, the emissions from enteric fermentation (GWPCH4ENT) are calculated according to the IPCC Tier 2 approach (based on animal numbers, feed intake in gross energy and methane conversion factors). However, the gross energy intake is not calculated using the formulas from the Tier 2 approach, as presented in Section 2. CAPRI is able to calculate endogenously the gross energy intake (from the summation of the different feed types fed to an animal: feed intake) and the new approach directly uses this figure. This has the advantage that the effects on gross energy intake (and hence also on methane emissions) of changes in the feed mix are endogenously considered in the system. In the previous approach such changes in the diet formulas would have been needed to be evaluated exogenously through changes in the ratio of digestible energy in a diet to gross energy consumed (DE%).

Additional to the use of the endogenous feed intake, the new approach for the calculation of GHG emissions also considers mitigation technologies endogenously. Whether the mitigation technology is put into practice as well as the magnitude of it are both a function of:

- the mitigation costs of each of the technologies,
- their revenues (if any, as in the case of anaerobic digesters (AD) which generate revenues through the selling of the produced biogas) and
- the subsidies obtained for their application.

Section 3 explains how the new features are considered in the calculation of methane emissions.

3.1 Total methane emissions from enteric fermentation with endogenous treatment of the feed mix and mitigation technologies

Equation 10 shows how CAPRI computes total methane emissions from enteric fermentation (*CH4ENT* in CO2 equivalents) in a region (set *RUNR*) and for an animal category (i.e. dairy cow).

First, the emission factor per unit of activity level (i.e. methane emissions per cow) is calculated. This is the sum over feed types, of the product of feed input coefficients (per feed type and unit of activity level) with emission factors (per feed type). In a second step, the obtained emission factor per unit of activity level is multiplied with the activity level (*v.actLevl*), which gives the total emissions per activity. Finally, those emissions are multiplied with a mitigation factor that contains the information on the level of emission reductions obtained from the "direct" mitigation technologies all together.

In this way, CAPRI is able to capture endogenously the consequences on methane emissions from enteric fermentation in two ways:

1. Indirect way: through mitigation options which indirectly reduce the amount of emissions (i.e breeding for increased feed efficiency).
2. Direct way or "end of pipe": through mitigation options which directly reduce the amount of emission (i.e. vaccination against methanogenic bacteria). This is the information captured in the mitigation factor.

Equation 10. Total methane emissions from enteric fermentation (by region, activity and level of intensity)

$$v.CO2EquEmis_{RUNR,MAACT,A,\text{"CH4ENT"}} = \left(\sum_{FEED} \mathrm{p.emisFeed}_{\mathrm{RUNR,MAACT,A,FEED,"CH4ENT"}} * v.feedInpCoeff_{RUNR,MAACT,A,FEED}\right) * v.actLevl_{RUNR,MAACT,A} * 0.001 * MC.GHG.Miti.Factor_{MAACT,A,\text{"}CH4ENT\text{"}}$$

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

A	Set for intensity level or "technology type": (i) T: mean technology, with IO coefficients as in data base / projection, (ii) T1: high yield variant with increased input demands per unit of output, and (iii) T2: low

	yield variant with decreased input demands per unit of output. Note that the T1/T2 distinction is currently (April 2018) only used for crops.
$v.CO2EquEmis_{RUNR,MAACT,A,\text{"CH4ENT"}}$	CO2 equivalent emissions from methane from enteric fermentation (CH4ENT) in a region (RUNR), for an animal production activity (MAACT) and an intensity level (A)
$\text{p. emisFeed}_{\text{RUNR,MAACT,A,FEED,CH4ENT}}$	CH4 emission coefficient per kg of feed type (FEED) in CO2 equivalent/kg
$v.feedInpCoeff_{RUNR,MAACT,A,FEED}$	Feeding of feed type (FEED) per head and year in kg
$v.actLevl_{RUNR,MAACT,A} * 0.001$	Level of production of an activity in 1000 ha or 1000 heads
$MC.GHG.Miti.Factor_{MAACT,A,CH4ENT}$	Influence of the mix of direct mitigation technologies on the methane emissions from enteric fermentation from an animal production activity (MAACT) and an intensity level (A)

Note that Equation 10 above is a simplification of the GAMS code. The equation in the code considers all animal production activities simultaneously (set *MAACT*) making use of "if" statements (the "$" signs in the code). Also, there is a sum over animal categories and technology types (A) which results in the total methane emission from enteric fermentation in a region. The corresponding code is presented in Figure 2 below.

Figure 2. Total methane emissions from enteric fermentation (the GAMS code)

```
*         -- standard version directly collects regional emissions:

    GWPCH4ENT_(RUNR)   ..
*
        v_CO2EquEmis(RUNR,"CH4ENT") =E=
*
            SUM( (R_RAGG(RUNR,MSACT),MAACT,A) $ p_technFact(RUNR,MAACT,"LEVL",A),
*                  Cattle depending on endogenous feed mix
                [  SUM(FEED $ p_maxFeedShare(RUNR,MAACT,A,FEED),
                      p_emisFeed(RUNR,MAACT,A,FEED,"CH4ENT")*v_feedInpCoeff(RUNR,MAACT,A,FEED)) $ (     CATACT(MAACT))
*                  non cattle is calculated according to tier 1
                +  EMISCALC(RUNR,MAACT,A,"CH4ENT","Y")                                        $ (NOT CATACT(MAACT))]
                * v_actLevl(RUNR,MAACT,A) * 0.001
*                  Influence of non dairy mitigation technologies
                * [MC_GHG_Miti_Factor(MAACT,"CH4ENT")           $ (not (sameas(MAACT,"DCOL") or sameas(MAACT,"DCOH")))
*                  Influence of Mitigation Technologies for Dairy Cattle
                 +MC_GHG_Miti_DCow(MAACT,"CH4ENT_3k","CH4ENT")   $ (     (sameas(MAACT,"DCOL") or sameas(MAACT,"DCOH")))]
*                  consider a reduction of energy need and emissions for sheep (not element of catAct) by option genet_eff:
                * [1+v_Miti(RUNR,MAACT,"genet_eff","rumFedEff")*p_ghgMiti(RUNR,MAACT,"genet_eff","othImpact","ENNE")
                                                                                                   $ PACT_TO_I(MAACT,"ILAM")]
              );
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Note also that the variable MC_GHG_Miti_Factor in Equation 10 and Figure 2 above is a macro which gathers the influence of all the direct mitigation technologies influencing the emissions of methane from enteric fermentation from an animal production activity. "Direct" in the sense that it takes into account the mitigation options which directly (and not indirectly) reduce the amount of emission, as mentioned above. For example, Figure 3 shows the effect of the macro MC_GHG_Miti_Factor for the case of the measure "vaccination against methanogenic bacteria" on emissions per unit of level for Belgium and for different cattle activities. In the reference (left column) MC_GHG_Miti_Factor = 1 for all activities, whereas it may be < 1 if subsidies trigger the implementation of vaccination (right column).

Figure 3. Methane emissions from enteric fermentation in the baseline and with the application of the measure "vaccination against methanogenic bacteria" (in Belgium, for selected animal categories, in kg/head)

Environmental indicators per activity [0]

Region: Belgium | Year: 2030 | Percentage diff. to Scen refpol_endotech_noc_sup | View type: Table

	refpol_endotech_noc_sup Methane emissions from enteric fermentation (IPCC) [kg/ha or hd]	subscal_endotech_vac Methane emissions from enteric fermentation (IPCC) [kg/ha or hd]
All cattle activities	98.63	93.56 -5.14%
Dairy Cows high yield	170.71	162.10 -5.04%
Dairy Cows low yield	125.87	119.52 -5.05%
Other Cows	74.51	70.74 -5.07%
Heifers breeding	82.33	78.13 -5.10%
Heifers fattening high weight	159.24	151.20 -5.05%
Heifers fattening low weight	92.14	87.52 -5.01%
Male adult cattle high weight	100.07	95.02 -5.05%
Male adult cattle low weight	50.12	47.59 -5.04%
Raising male calves	28.05	26.64 -5.03%
Raising female Calves	25.66	24.37 -5.03%
Fattening male calves	13.31	12.64 -5.04%
Fattening female calves	20.97	19.91 -5.04%

Extracted from the GUI from the table "environmental indicators per activity"

3.2 Endogenous consideration of the mitigation technologies

3.2.1 Generalized structure

In the context of a study for the IPTS[3] ("Quantitative assessment of potential GHG mitigation policy options in the agricultural sector, and their production and economic implications") under an ENgAGE framework contract, mitigation options from GAINS have been included (endogenized) into the regional supply models of CAPRI.

The mitigation measures are endogenized in two ways, a direct and indirect one, as mentioned before. The direct way works with technical coefficients ($mfac_{ACT,a,e}$), which "directly" reduce the level of the original emission factors ($\varepsilon_{ACT,a,e}$) that provide the information on emissions without the influence of any mitigation technology. The indirect way reduced the level of emissions through increases in efficiency in the production systems. For example, through changes in the feed mix that reduce the gross energy intake or through enhanced application of fertilizers.

These technical coefficients and emission factors are specified for: (i) each production activity (*ACT*), (ii) each production technology variant (a) which indicates high or low intensity and (iii) the emission type (e) that, in this case, is methane from enteric fermentation ($CH4ENT$). The emission factors $\varepsilon_{ACT,a,e}$ give the amount of an emission type for one unit of the activity (i.e. per dairy cow/year). The technical coefficients $mfac_{MAACT,a,e}$ contain the information on the savings of an emission type (methane emissions from enteric fermentation) obtained from the mix of mitigation options applied, (also per unit of level: for one unit of the activity). To get total amount of emissions of type '*e*' from an animal production activity, one multiplies the emissions at unit level with the activity level (the output of the activity in a region), as follows:

Equation 11. Generalized calculation of total emissions (by region, emission type, activity and level of intensity)

$$emi_{e,ACT} = \sum_{a} \varepsilon_{e,ACT,a} \cdot mfac_{e,ACT,a} \cdot actLevl_{ACT,a}$$

Location in CAPRI file structure: no specific location since this is a generalized formulation

Note: the regional set RUNR is omitted from the equation to improve readability

[3] Institute for Prospective Technological Studies (IPTS), Joint Research Centre (JRC), European Commission, Sevilla, Spain

Where:

a	Set for intensity level or "technology type"
$emi_{e,ACT}$	Total emissions of type (e) from an activity (ACT) in a region (RUNR) in CO2 equivalent emissions
$\varepsilon_{e,ACT,a}$	Original emission factor per unit of level (for one unit of the activity, i.e. emissions per dairy cow/year), without the effect of any mitigation technology, for emission type (e) for an activity (ACT) of intensity level (a) in a region (RUNR)
$mfac_{e,ACT,a}$	Technical coefficient or mitigation factor (also per unit of level) containing the information on the savings on an emission type obtained from the mix of mitigation options applied for an activity (ACT) of intensity level (a) in a region (RUNR)
$actLevl_{ACT,a}$	Level of production of an activity (ACT) of intensity (a) in a region (RUNR) in 1000 ha or 1000 heads

Note that the structure of the equation for the calculation of total methane emissions from enteric fermentation (Equation 10) is very similar to equation above. The difference is only that the original emission factor ε from Equation 10 is composed of several emission factors, one for each of the feed types.

Now, the question arises: how is it that the technical coefficient *mfac* contains the information on the emission savings (per unit of level) obtained from the mix of mitigation options applied for an activity (ACT) of intensity level (a) in a region (RUNR)? To answer this question let us analyze the components of the mitigation factor.

Equation 12. The mitigation factor (*mfac*)

$$mfac_{e,ACT,a} = \sum_{m} \mu_{e,ACT,a,m} \cdot mshar_{e,ACT,a,m}$$

Subjec to: $$0 \leq mshar_{e,ACT,a,m} \leq 1$$

$$\sum\nolimits_{m\_map} mshar_{e,ACT,a,m} = 1$$

Location in CAPRI file structure of "*mfact*": '…CapriTrunk\gams\supply\ghg_miti_macros.gms'

Location in CAPRI file structure of $\sum_{m\_map} mshar_{e,ACT,a,m} = 1$: '…CapriTrunk\gams\supply\supply_model.gms', after the comment "constraints for implementation of mitigation options"

Where:

$\mu_{e,ACT,a,m}$ The reduction factor (per unit of level) applied to $\varepsilon_{e,ACT,a}$ (the original emission factor). It is obtained from the application of mitigation technology (m) in a determined region, for emissions of type (e) from activity (ACT) of level of intensity (a). The factor gives the mitigation capacity as if the mitigation measure was fully implemented in the region under consideration.

$mshar_{e,ACT,a,m}$ The implementation share of the mitigation measure (m) in a determined region, for emissions of type (e) from activity (ACT) of level of intensity (a)

m_map A set containing a mapping between emission types (e), activity levels (ACT) and mitigation measures (m) considered in the second constraint from above (sum of mitigation shares must add to 1). The mapping ensures that mitigation measures targeting the same emission type are not applied simultaneously, except if a combination is explicitly foreseen.
For the emission type CH4ENT (methane from enteric fermentation), the mitigation measures active in the mapping are:
(i) vaccination against methanogenic bacteria,
(ii) nitrate as a feed additive,
(iii) linseed as a feed additive,
(iv) the combined application of nitrate and linseed as feed additives and
(ii) no control (NOC), which indicates “no mitigation control” and is an element of the set of mitigation measures.
NOC is used to ensure that the constraint holds. It takes the remaining share (if applicable) to get the sum of mitigation shares to add to 1.
The mitigation measures not included in the mapping are ignored in the constraint.
The measure ‘breeding for increased feed efficiency’ is not included in the mapping of measures targeting CH4ENT even though it also targets this emission type. This reflects the assumption that it may be combined with any of the other measures such that, for example, genetically improved cattle may also receive feed additives.

Note that the reduction factor μ specifies the reduction from the total of emissions of type (e) (per unit of level) obtained from the full application of a mitigation technology in a determined region (i.e., the following hypothetical value: a total of 10% reduction of methane emission from enteric fermentation from the full implementation of vaccinations against methanogenic bacteria in a determined region). The *mshar* indicates the share of implementation of the mitigation measure ($0 \leq mshar_{e,ACT,a,m} \leq 1$). In this way, the effect of each of the mitigation measures on total emissions of type (e) is captured. By adding the effects of each of the measures considered for an emission type (e) one gets the total effect ($mfac_{e,ACT,a}$) per emission type, activity and level of intensity in a determined region.

The reduction factors $\mu_{e,ACT,a,m}$ are exogenous variables whose values are computed based on external information sources as the GAINS[4] database and the AnimalChange[5] project. The implementation share of a mitigation technology is an endogenous variable and it is a function of its mitigation costs, the revenue generated by it (if any, as in the case of AD) and the subsidy (or tax) to which it is subject. The details of its determination are explained below.

3.2.2 Endogenous determination of the implementation share of a mitigation technology

The net cost function of mitigation measures: concept and parameter specification

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. 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 if production of a certain commodity (i.e. maize) is expanded. These other costs may appear due to, for example, bottlenecks of labor and machinery (so that production cannot be deliberately expanded without increasing the costs per unit of the product), or potentially also risk premiums. Due to these non-linear costs, farmers will neither suddenly nor to a large extent switch from barley to maize production even if in a scenario net revenues of maize may happen to increase beyond those of barley. A sudden and large switch to the production of a more profitable commodity (like maize instead of barley) would be the outcome of a linear programming model, but it is rarely observed in statistics. Therefore, CAPRI uses a nonlinear cost function to reflect the rather smooth responsiveness to incentives. These nonlinear costs are often called "calibration costs" and are a well-established and commonly used modelling approach (Heckelei et al. 2012). For brevity and in acknowledgement of their origin in the positive mathematical programming approach they are called ‘pmp costs’ here (and in CAPRI result tables).

For activity levels or for supply and demand quantities (i.e. in the production of a certain crop), “responsiveness” to economic and political incentives is often expressed in terms of elasticities. These give the percentage increase in an activity level if its output price is increasing by 1 %. For technological mitigation measures elasticities are not a convenient indicator of responsiveness, because most observed mitigation shares (in particular for future technologies) are zero in the base

[4] GAINS (short for "Greenhouse Gas and Air Pollution Interactions and Synergies") database provides mitigation technologies and their cost structure. GAINS is a model describing the evolution of various pollutants and their abatement options developed by the International Institute for Applied Systems Analysis (IIASA) and used by several services in the European Commission, see http://gains.iiasa.ac.at/. Due to the limited involvement of GAINS staff in making use of their database, the responsibility for the correct interpretation of this information relies with the authors of the CAPRI studies.
[5] http://www.animalchange.eu/

year, and therefore elasticities cannot be defined. Instead, the responsiveness of the application of a certain mitigation technology to incentives is based on theoretical considerations.

To simplify the exposition, we consider the choice of the mitigation share for a single fixed activity where a mitigation measure: (i) implies a certain amount of mitigation costs, (ii) receives a subsidy S (which is zero in the observed situation) and (iii) potentially generates a revenue R (i.e. from energy produced in AD plants). This problem is solved by finding the minimization point of the net cost function of a mitigation measure.

Equation 13. Minimization of the net cost function of a mitigation measure per region, activity and emission type (per unit of level)

$$\min N_{ACT,m,e}(mshar_{ACT,m,e}) = C_{ACT,m,e}(mshar_{a,m,e}) - S_{ACT,m,e} \cdot mshar_{ACT,m,e} - R_{ACT,m,e} \cdot mshar_{ACT,m,e}$$

Note 1: to improve readability, the index for the regional set is omitted.

Note 2: the net costs are per unit of level, which indicates the costs for the application of the mitigation measure to one unit of the production activity (i.e. per hectare or per cow). Thus, to obtain the total net costs, the net costs should be multiplied with the regional activity levels.

Location of the net cost function in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

$N_{ACT,m,e}(mshar_{ACT,m,e})$	Net cost function (costs minus subsidies and revenues) of a mitigation measure per region, activity (ACT) and emission type (e) (per unit of level). The variable (N) is a function of the mitigation share (mshar).
$C_{ACT,m,e}(mshar_{a,m,e})$	Cost function of a mitigation measure per region, activity (ACT) and emission type (e) (per unit of level). The variable (C) is a function of the mitigation share (mshar).
$S_{ACT,m,e}$	Subsidy for the implementation of the mitigation option (m) (per unit of level).
$mshar_{ACT,m,e}$	Mitigation share of mitigation option (m) applied in the production activity (ACT) for the reduction of emissions type (e).
$R_{ACT,m,e}$	Revenue from the implementation of the mitigation option (m) (per unit of level).

As mentioned above, the specification of the mitigations costs in CAPRI ($C_{ACT,m,e}$) is split into a part with given cost (from GAINS or other sources) and other costs that are not observed and potentially specific to each farmer. This "pmp costs" go beyond the "accounting costs" based on hard information and are related to multiple determinants for technology adoption:

Equation 14. Cost function of a mitigation measure per region, activity and emission type (per unit of level)

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

Note 1: to simplify the exposition, the pmp costs (linear and quadratic) are omitted.

Note 2: to improve readability, the index for the regional set is omitted.

Note 3: the net costs are per unit of level, which indicates the costs for the application of the mitigation measure to one unit of the production activity (i.e. per hectare or per cow). Thus, to obtain the total net costs, the net costs should be multiplied with the regional activity levels.

Location in the CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

This cost equation is part of the net cost function in the GAMS code.

Where:

$\kappa_{ACT,m,e}$	Accounting costs (per unit of activity) for the full implementation of mitigation option (m) in the production activity (ACT) and for the reduction of emissions of type (e).
$\lambda_{ACT,m,e}$	Parameter for non-constant accounting costs (per unit of activity) for the full implementation of mitigation option (m) in the production activity (ACT) and for the reduction of emissions of type (e). $\lambda_{ACT,m,e} = 0$ for all mitigation options expect for AD.
$\beta_{ACT,m,e}$ and $\gamma_{ACT,m,e}$	Additional costs parameters that are determined in the calibration of the mitigation costs function.

For the determination of the additional cost parameters $\beta_{ACT,m,e}$ and $\gamma_{ACT,m,e}$, three cases have to be distinguished: (i) and (ii) depending on whether or not the mitigation technology is already applied in the base year, and (iii) for the cases where the mitigation measures generate benefits which are not explicit (as revenues) and are thus estimated with an alternative method.

(i) Parameter specification of the net cost function of mitigation measures: the case when the mitigation technology is already adopted in the base year

To determine the two unknown additional cost parameters $\beta_{ACT,m,e}$ and $\gamma_{ACT,m,e}$ we use two conditions (cf. Figure 4). The first one is the first order condition for the minimization of net costs at the observed mitigation share (here assumed to be > 0):

Equation 15. First order condition for the minimization of net costs at the observed mitigation share

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

Where:

$mshar^{0}_{ACT,m,e}$ Current mitigation share according to the GAINS database (m0 in Figure 4).

The second condition is an assumption related to responsiveness: for a certain subsidy (S1), the optimal solution is the implementation of the mitigation technology up to the technical limit (full implementation). Thus, $mshar^{1}_{ACT,m,e} = mshar^{max}_{ACT,m,e}$ which is represented by the point m1 in Figure 4.

With the payment of the subsidy (S1), the first order condition for minimization of the net costs must also be zero at the maximum implementation share.

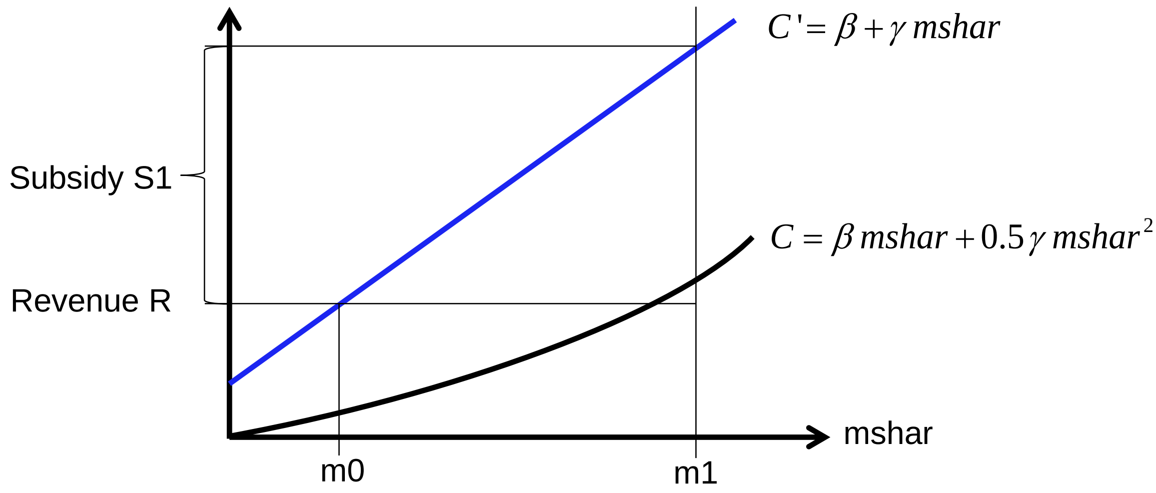
Equation 16. First order condition for the minimization of net costs at the maximum mitigation share

$$\frac{\partial N(mshar^{1}_{ACT,m,e})}{\partial mshar^{1}_{ACT,m,e}} = \frac{\partial C(mshar^{1}_{ACT,m,e})}{\partial mshar^{1}_{ACT,m,e}} - S^{1}_{ACT,m,e} - R_{ACT,m,e} = 0$$

$$\Rightarrow \quad = \kappa_{ACT,m,e} + \beta_{ACT,m,e} + (\lambda_{ACT,m,e} + \gamma_{ACT,m,e}) mshar^{1}_{a,m,e} - S^{1}_{ACT,m,e} - R_{ACT,m,e} = 0$$

This is the second condition needed to specify a nonlinear cost function with smooth behavior of uptake of the technological mitigation options. Note that parameter $\lambda_{ACT,m,e} = 0$ for all options except AD. In the graphical representation of the calibration problem with a positive implementation in the baseline it is assumed that the initial subsidy S0 is zero and that the accounting costs $\kappa_{ACT,m,e} = 0$ as well (or that it is already merged into the revenues $R_{ACT,m,e}$). A positive baseline implementation and the existence of revenues is typical for the case of AD.

Figure 4. Representation of a mitigation cost curve in CAPRI with positive initial implementation



At the initial implementation share (with mshar = m0) Equation 15 holds, such that marginal cost equals revenue (C' = R). If in addition to R, farmers would receive the subsidy S1, Equation 16 holds at mshar = m1 as well (assuming that $\lambda_{ACT,m,e} = \kappa_{ACT,m,e} = 0$), representing the case of full implementation.

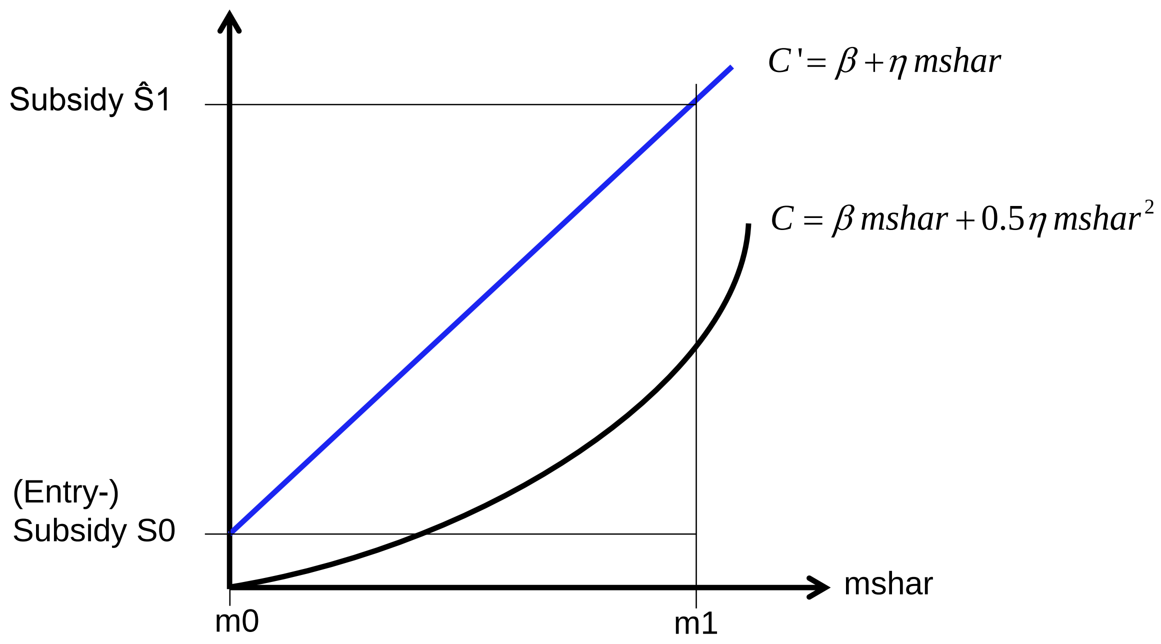
A key assumption is the level of the subsidy at which "full implementation" is achieved. For the time being, it is assumed that the implementation of a mitigation technology is at its maximum if a relative subsidy of 80% of the accounting costs from GAINS is paid. Thus $S^1_{ACT,m,e} = 80\% \cdot \kappa_{ACT,m,e}$. The assumption of 80% reflects the responsiveness of the farming sector towards incentives for applying the technology. If a lower relative subsidy would be assumed (i.e. only 10%), this would mean that farmers would quickly adopt the technology completely. If a higher relative subsidy would be assumed (i.e. >100%), this would mean that for those farmers that are "late followers" of adopting the technology, there are unknown additional impediments, requiring compensation beyond the accounting cost, even though for some "early adopters" there are apparently unknown benefits that more than outweigh the standard accounting cost $\kappa_{ACT,m,e}$, considering that this was the case of a positive observed implementation.

The exposition shows how the share of implementation of a mitigation measure is endogenized as a function of costs and revenues.

(ii) Parameter specification of the net cost function of mitigation measures: the case when the mitigation technology is not adopted in the base year

The case of zero implementation shares in the baseline is more common than the case described above. This holds in particular for newly developed (or considered) technologies. Zero implementation of a mitigation technology implies that it is currently not attractive for farmers to apply the technology. If farmers could choose a negative share and earn the marginal cost as revenue they would like to do so. To reflect that this non-negativity condition is typically binding in these cases, it is assumed that an entry (relative) subsidy of $S^0_{ACT,m,e} = 20\%$ of the accounting costs is needed to make the technology attractive for the first adopter. Furthermore, as the technological mitigation options with observed zero shares in the base year are apparently less attractive to farmers, the implementation by “late followers” may only be expected at a higher subsidy rate than S1 from above. Our assumption for these cases is 120% (rather than the assumed 80% for those technologies already applied in the base year). This implies that the uptake of these mitigation technologies by “late followers” is subject to higher unobserved costs (i.e. risks or lack of technical knowledge). Thus, it is assumed that higher incentives are needed in order to achieve full implementation. This case is depicted in Figure 5.

Figure 5. Representation of a mitigation cost curve in CAPRI with zero initial implementation



In Figure 5, it has been assumed that the costs are positive for all positive implementation shares and that the constant (β) is the same as in Figure 4. However, the slope of the marginal cost curve (in this case denominated by η, with the purpose of distinguishing it better) is higher. Also, it is assumed that the mitigation measure does not produce any revenues and that a positive entry subsidy ($S0 = \beta = 20\%$) is needed in order to make Equation 15 hold (at m0). At this point, the first farmer is indifferent between adopting or not adopting. The slope η can be obtained from solving Equation 16 at S1 = 120%, as well as: $\beta = 20\%$, mshar = 100%, and $\kappa_{ACT,m,e} = \lambda_{ACT,m,e} = R_{ACT,m,e} = 0$.

(iii) Parameter specification of the net cost function of mitigation measures: the case when the mitigation technology generates benefits which are not explicit (as revenues)

This parametrization method is independent of whether the mitigation technology is already adopted in the base year or not. It can be applied in both cases.

Some mitigation technologies generate benefits which are not explicit (as revenues). In consequence, these 'implicit revenues' cannot be used in the minimization problem from Equation 13 (minimization of net costs of a mitigation measure). Currently, from the mitigation options, the feed and breeding options are considered to generated "implicit" benefits, namely:

- Low nitrogen feeding
- Feed additives: nitrate
- Feed additives: linseed
- Breeding for increased feed efficiency
- Breeding for increased milk yields

Though, note that in this documentation the mitigation measures 'low nitrogen feeding' and 'breeding for increased milk yields' are not presented in detail since they do not directly target the reduction of methane from enteric fermentation.

The feed and breeding technologies presented above generate benefits through the saving of costs. For example, with the supplementation of nitrate or linseed in the feed, less protein or fat feedstuffs are required respectively. For the breeding options, less feed per unit of output (per head and subsequently per unit of meat or milk) is required. However, the quantification of the magnitude of the saved costs is complex due to the several feed restrictions. For example, equality restrictions on feed energy and protein and several inequality restrictions for single feed stuffs, dry matter components, lysine, and fiber fractions. Moreover, at the regional level roughage fed to animals needs to be produced in that same quantity, establishing a link to the crop sector. In consequence, the assessment of any feed cost savings or other economic effects are carried out with two auxiliary scenarios which help to determine the "implicit marginal benefits" at the initial mitigation share (normally zero -mitigation technology is not adopted in the base year-) and at the maximum implementation shares.

In the first auxiliary scenario, all mitigation cost entries are removed from the model such that the technical mitigation options are available "for free", but the mitigation shares are tightly constrained around their initial values (i.e., very close to zero but leaving a small scope of freedom –very small interval of mitigation share possibilities– in order to make it possible for the solver to estimate a marginal value; see gams\supply\set_miti_bounds.gms). Then, the reference scenario is run again but including these settings and with the global "market model" switched off. The resulting marginal values (given in the GAMS output and saved in the 'costsavings_ini_21230_jul15.gdx' file) of the above constraints for the different mitigation technologies indicate the marginal economic benefit (or cost) of each of the options (if the share of each of them were to be slightly increased). These values quantify the full economic benefit (or cost) of each of the options, taking into account the supply model equations in their full complexity.

In the second auxiliary scenario the same as in the first one is done but in this case with the implementation shares of the corresponding measures tightly constrained close to their maximum bounds. This gives the marginal values (implicit benefits) of the mitigation options when implementation is close to its maximum, again considering the full complexity of the supply models.

Having obtained these marginal values that estimate the implicit benefit of the measures around their initial and maximum implementation shares, they may be treated as revenues in the problem of minimization of the net costs from Equation 13 and the first order conditions at the observed initial mitigation share and at the maximum share (Equation 15 and Equation 16 respectively) can be solved. In this way the two unknown additional cost parameters $\beta_{ACT,m,e}$ and $\gamma_{ACT,m,e}$ from the cost function (see Equation 14) are determined and we obtain fully calibrated mitigation cost curves that consider the 'implicit' benefits of the mitigation technologies.

As an example, Figure 6 shows the obtained parameters of the mitigation cost function for the option 'feed additivies: nitrate' dairy cows of high yield (DCOH) in selected NUTS 2 regions. The columns 'costsaving0' and 'costsaving1' give the marginal values from the two auxiliary scenarios. That the values from costsaving1 are normally lower than those from costsaving0 is typical, as the marginal value of the mitigation options usually declines with increasing implementation.

Figure 6. Mitigation cost function parameters for the option 'feed additives: nitrate' for dairy cows of high yield (DCOH) for selected NUTS 2 regions

p_ghgMiti (C:\GAMS-Models\CapriTrunk\output\after2016\permits\res_ghg_subscal_endotech_nitr_21230.gdx) [0]

Dim1 (SWHE,DWHE,..): DCOH; Dim2 (NOC,COMB2_RICE,..): Nitr_Tot; Dim3 (N2OSYN,N2OHIS,..): CH4ENT; View type: Table

	costParLin	costsaving0	costsaving1	pmpParLin	pmpParSqr
DK000000	613	3226	2959	2644	618
BL210000	613	3045	2552	2463	412
BL220000	613	3045	2302	2463	120
DE110000	613	3022	-5405	2441	285
DE120000	613	3022	2304	2440	79
ES110000	613	3227	2585	2645	75
ES120000	613	3227	2496	2645	74
FR210000	613	2671	2086	2089	201
FR220000	613	2671	1965	2089	102
IT200000	613	3347	2849	2765	275
IT400000	613	3347	2499	2765	81
NL110000	613	3028	2465	2447	264
NL120000	613	3028	2587	2447	495
UKF00000	613	4033	3634	3451	588
UKG00000	613	4032	3695	3451	705

How to get to this table in the GUI: utilities\GDX Viewer\Load gdx file\"browse and select the desired file"\"through right click on the icon for pivot table arrange the table as desired".

In Figure 6, the case of DE110000 (Stuttgart) illustrates a frequent problem: A full implementation may be infeasible or very unfavorable (negative implicit benefits) for single regions and animal types. Infeasibility has been avoided by an automatic relaxation of the calibration bounds on the mitigation shares (in gams\supply\widen_bounds.gms), however the case of a feasible, but unreasonable implementation is not (yet) solved. With 276 regions, 18 animal activities and several mitigation options involving endogenous calculations of cost savings it is also infeasible to analyze each of these problem cases in detail. Instead the standard solution of equations 15 and 16 is used in general to obtain the unknown slope parameter $\gamma_{ACT,m,e}$ = pmpParSqr. But in some cases very strongly declining or even negative entries for "costsaving1" may generate negative results for parameter $\gamma_{ACT,m,e}$ (giving downward sloping marginal cost). In this case a fallback rule is applied: the resulting parameter $\gamma_{ACT,m,e}$ is set to 5% of the (positive) accounting costs, with parameter $\beta_{ACT,m,e}$ adjusted accordingly. In these cases, the model will not reproduce the maximum share even with subsidies granted as in the second auxiliary scenario, but it will reproduce the initial shares and respond in a regular way.

The net cost function of mitigation measures: GAMS code

The net cost function presented in the minimization problem of Equation 13 and Equation 14 can also be found in the GAMS code of CAPRI. Though, in the GAMS code the equation captures the net costs of all mitigation measures together for a determined region. Also, more details are shown: (i) the linear and non-constant pmp costs (the unobserved costs), (ii) the transformation from unit to total costs per region and (ii) a special penalty part to control total fat content on feed intake. In the code, the equation is divided into 8 parts, which are presented below. Also, note that the equation in the code is simply called "mitigation cost function" and not "net cost function". In this section, in order to go along with the code, it is also only called mitigation cost function.

Figure 7. Mitigation cost function part 1: observed accounting costs per unit of activity

```
*      -- standard version of mitigation cost function directly collects total accounting and pmp costs :
*
    GHG_Mit_Cost_(RUNR).. v_GHG_Mit_Cost(RUNR)   =E=

     sum{(R_RAGG(RUNR,MSACT),mitiTech_map(MSACT,PACT,allMitiTech,mitiTarget)),

*          - first part is the observed accounting cost per activity level

           [ (    p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"costParLin")
               + p_ghgMiti(MSACT,PACT,allMitiTech,mitiTarget,"costParLin")
               $ (NOT p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"costParLin"))) * v_Miti(RUNR,PACT,allMitiTech,mitiTarget)

*          ... except for the option GENET_REP which is expressed relative to the young cow price, see envind\breeding.gms

           * (1                                                                          $ (NOT SAMEAS(allMitiTech,"Genet_rep"))
             +(%data%(MSACT,"UVAG","YCOW","Y") $ (not p_useUvagScen) + (p_uvagScen(MSACT,"YCOW") $ p_useUvagScen) )
                                                                                         $      SAMEAS(allMitiTech,"Genet_rep") )
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

GHG_Mit_Cost_(RUNR)..	Equation name
v_GHG_Mit_Cost(RUNR)	Total mitigation cost variable in a region (RUNR) (i.e. a NUTS2 region)
R_RAGG(RUNR,MSACT)	Dynamic set containing the regions actively running as i.e. NUTS2 (RUNR), for the Member State currently active (MSACT)
mitiTech_map (MSACT,PACT,allMitiTech,mitiTarget)	Dynamic set linking admissible mitigation technologies (allMitiTech) to the member state (MSACT), production activities (PACT) and target variable as i.e. CH4ENT (mitiTarget)
p_ghgMiti (RUNR,PACT,allMitiTech,mitiTarget,"costParLin")	Linear accounting costs (per unit of activity) for the full implementation of mitigation option (allMitiTech) in the production activity (PACT) and for the reduction of emissions of type (mitiTarget). Value based on GAINS database and other sources.
p_ghgMiti (MSACT,PACT,allMitiTech,mitiTarget,"costParLin")	Additional cost parameter used only in the case that there is no entry for p_ghgMiti("RUNR",*,*,*) for the NUTS2 regions currently active. Then, the parameter at the member state level is taken (p_ghgMiti("MSACT",*,*,*)).

v_Miti(RUNR,PACT,allMitiTech,mitiTarget) — Implementation shares for GHG mitigation by region, activity, mitigation option and target variable

Note: Note that in the case of the mitigation option "GENET_REP" (Genetic improvements reducing the cow replacement rate), an additional coefficient is included in this part of the cost function. The coefficient puts the mitigation costs relative to the young cow price.

Figure 8. Mitigation cost function part 2: observed quadratic component

```
*          - second part is the observed component quadratic in mitigation shares  (mitigation option AD_anCh)

         + .5 * (  p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"costParSqr")
                +  p_ghgMiti(MSACT,PACT,allMitiTech,mitiTarget,"costParSqr")
                $  (NOT p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"costParSqr"))) * sqr(v_Miti(RUNR,PACT,allMitiTech,mitiTarget))
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

p_ghgMiti (RUNR,PACT,allMitiTech,mitiTarget," costParSqr") — Parameter for non-constant accounting costs (per unit of activity) for the full implementation of mitigation option (allMitiTech) in the production activity (PACT) and for the reduction of emissions of type (mitiTarget). This parameter is = 0 for all mitigation options expect for AD.

sqr(v_Miti(*,*,*,*)) — Square root of the implementation shares

Figure 9. Mitigation cost function part 3: observed accounting revenues from anaerobic digestion per unit of activity

```
*          - third part is the observed accounting revenues per activity level  (mitigation option AD_anCh)

         - (   p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"revenue")
            + p_ghgMiti(MSACT,PACT,allMitiTech,mitiTarget,"revenue")
            $  (NOT p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"revenue"))) * v_Miti(RUNR,PACT,allMitiTech,mitiTarget)
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

p_ghgMiti(RUNR,*,*,*,"revenue") — Revenues from mitigation technology [€/unit of activity]. The "revenue" position is currently only populated for AD_anCh (Farm-scale anaerobic digestion plants as used in the Animal Change Project (not based on GAINS)).

Figure 10. Mitigation cost function part 4: unobserved linear component per unit of activity

```
*          - fourth part is the unobserved component linear in mitigation shares

         + (    p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"pmpParLin")
              + p_ghgMiti(MSACT,PACT,allMitiTech,mitiTarget,"pmpParLin")
              $ (NOT p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"pmpParLin"))) * v_Miti(RUNR,PACT,allMitiTech,mitiTarget)
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

p_ghgMiti(RUNR,*,*,*,"pmpParLin")	Unobserved linear costs (per unit of activity) for the full implementation of mitigation option (allMitiTech) in the production activity (PACT) and for the reduction of emissions of type (mitiTarget).

Figure 11. Mitigation cost function part 5: unobserved quadratic component per unit of activity

```
*          - sixth part is the unobserved component quadratic in mitigation shares

         + .5 * (   p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"pmpParSqr")
                  + p_ghgMiti(MSACT,PACT,allMitiTech,mitiTarget,"pmpParSqr")
                  $ (NOT p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"pmpParSqr"))) * sqr(v_Miti(RUNR,PACT,allMitiTech,mitiTarget))
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

p_ghgMiti(RUNR,*,*,*,"pmpParSqr")	Unobserved non-constant costs (per unit of activity) for the full implementation of mitigation option (allMitiTech) in the production activity (PACT) and for the reduction of emissions of type (mitiTarget).

Figure 12. Mitigation cost function part 6: deduction of subsidies

```
*          - seventh part is a deduction of subsidies linear in mitigation shares

         - (    p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"subsidy")
              + p_ghgMiti(MSACT,PACT,allMitiTech,mitiTarget,"subsidy")
              $ (NOT p_ghgMiti(RUNR,PACT,allMitiTech,mitiTarget,"subsidy"))) * v_Miti(RUNR,PACT,allMitiTech,mitiTarget)

           ]
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

p_ghgMiti(RUNR,*,*,*,"subsidy")	Subsidy for the implementation of the mitigation option (per unit of level).

Figure 13. Mitgation cost function part 7: transformation from unit to total costs per region

```
*          - and all needs to be multiplied by activity levels
*
        * [   sum(A $ (p_technFact(RUNR,PACT,"LEVL",A) $ AACT(PACT)),
              v_actLevl(RUNR,PACT,A)
*                 consider that costs are expressed per animal stock (HEAD) not flow (LEVL) in GAINS data
              * ( (p_animProdDays(RUNR,PACT,"T")/365)                 $ (not SupplTech(allMitiTech))
*                 Dry Matter consumption times Fat share of Dry matter = Fat consumption
                + (p_animReq(RUNR,PACT,"T","DRMA") * p_animProdDays(RUNR,PACT,"T") / 1000
                    * p_emisFeed(RUNR,PACT,"T",allMitiTech,"ShrOfDM")) $ ( (sameas(allMitiTech,"Line_Tot") or sameas(allMitiTech,"Nitr_Tot"))
                                                                        $ catact(PACT)
                                                                        $ mitiTech_map(MSACT,PACT,allMitiTech,"CH4ENT")))
                )

*            ... or by the regional histosol area
            + p_ghgMiti(RUNR,"ISET","fallow","othImpact","UAAR")*%data%(runr,"UAAR","LEVL","Y") $ sameas(PACT,"ISET")

*            ... or simply the activity level for increased legume share in temporary grasland or rice measures
            + sum(A $ p_technFact(RUNR,PACT,"LEVL",A),v_actLevl(RUNR,PACT,A))                   $ (sameas(PACT,"OFAR") or sameas(PACT,"PARI"))

*            ... or in the case of crop (and fertiliser) related mitigation by total mineral fertiliser use of nitrogen

            - v_netPutQuant(RUNR,"NITF")                                                         $ sameas(PACT,"cropMiti")

*            ... or in the case of fertiliser measures on grasland by total mineral fertiliser use of nitrogen on GRAS and OFAR

            + (  v_fertDist(RUNR,"OFAR","NITF","Mine")
$if not %NMINREST% == on      + v_fertDist(RUNR,"GRAS","NITF","Mine")
$if %NMINREST% == on          + v_fertDist(RUNR,"GRAE","NITF","Mine") + v_fertDist(RUNR,"GRAI","NITF","Mine")
                                                                                       ) $ sameas(PACT,"grasMiti")

          ]
        }
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

A	Set for intensity of production or "technology type": (i) T: mean technology, with IO coefficients as in data base / projection, (ii) T1: high yield variant with increased input demands per unit of output, and (iii) T2: low yield variant with decreased input demands per unit of output
v_actLevl(RUNR,PACT,A)	Level of production of the activities in 1000 ha or 1000 heads
p_animProdDays(RUNR,PACT,"T")	Total days of production for animals (for supply model and LEVL to HERD linkage) with mean technology 'T' (= only type used for animals)
p_animReq(RUNR,PACT,"T","DRMA")	Animal requirement of dry matter (DM) per unit of activity (per head)
p_emisFeed(RUNR,PACT,"T",allMitiTech,"ShrOfDM")	The cost parameter used in the previous parts (for feed additive technologies as adding lineseed to improve feed efficiency) is expressed per tonne of feed additives. The maximum feed additives intake (in tons) is in turn calculated as a share of DM intake. DM intake follows from DM intake in kg per day multiplied with production days (and divided by 1000 to convert from kg to tons).
p_ghgMiti(RUNR,"ISET","fallow","othImpact","UAAR")	Various items to specify GHG mitigation based on GAINS data. In this case with respect to histosols area.

ISET	Set aside obligatory idling
Fallow	Fallow of histosol land
othImpact	Impacts on variables other than the direct targets
UAAR	Utilizable agricultural area
%data%(runr,"UAAR","LEVL","Y")	Data on regional level of UAAR in simulation year "Y"

Note that this part of the equation (

Figure 13) transforms the costs from unit to total costs per region and that it captures all type of mitigation technologies through the use of gams "sets" and "if" statements. For example, in the case of feed additives (i.e. linseed or nitrate), the cost parameter used in the previous parts of the mitigation cost function (per unit of level) is expressed per tonne of feed additives. Thus, to obtain the total costs, the unit cost parameter (obtained from GAINS) must be multiplied with the total tonnes of feed additive consumed by the total of animals (actLevl). The total tonnes of feed additive is calculated by multiplying the actLevl with the fat consumed as a result of the application of the feed additive technology (which is obtained as a share from dry matter consumed). For the computation of these costs, the other parts of the equation from

Figure 13 are not active (through the use of "if" statements: the $ signs).

In a similar way, the other parts of the equation are active or not (corresponding with the mitigation measure active). This parts are marked by the comments in grey font: (i) *"and all needs to be multiplied by activity levels"*, (ii) *"... or by the regional histosol area"*, (iii) *"... or simply the activity level for increased legume share in temporary grasland or rice measures"*, (iv) etcetera.

Figure 14. Mitigation cost function part 8: special penalty part to control total fat content on feed intake

```
*          - special penalty part to control total fat content of feed intake
*
   + sum{ (R_RAGG(RUNR,MSACT),mitiTech_map(MSACT,AACT,"Line_Tot",mitiTarget),A) $ p_technFact(RUNR,AACT,"LEVL",A),
*                    soft constraint shall only be active if Line_Tot is used (e.g. not in reference scenario):
                     sqr(v_Miti(RUNR,AACT,"Line_Tot",mitiTarget))
                   * v_actLevl(RUNR,AACT,A)
                   * p_animReq(RUNR,AACT,"T","DRMA") * p_animProdDays(RUNR,AACT,"T") / 1000
                   * v_supplementSlack(RUNR,AACT,"Line_Tot")
                   * 999999}
;
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

"line_Tot"	Sum of lineseed and a combination of lineseed and nitrate fed to the animals in order to reduce CH4 emissions from Enteric Fermentation
v_supplementSlack(RUNR,AACT,"Line_Tot")	Slack variable becoming positive if the fat added with feed supplements to the dry matter intake is above the 5% threshold, which is heavily penalized. This is a technical "trick" to impose the maximum share of feed additives intake, defined in "SupplementPerc_", without specifying a hard bound.

Part 8 of the mitigation cost function above is a "trick" not to allow the system of endogenous mitigation measures to use shares of feed additive options (feeding additional lipids from Linseed (OFLA)) that would result in feed supplements above a heavily penalized threshold. The trick works through the use of the variable v_supplementSlack. This slack variable takes the value 0 if the share of fat added with the additives is below 5% of the dry matter intake, and it takes positive values if the share of fat added is above the 5% threshold. This occurs since the variable 'v_supplementPerc(…)' from Figure 15 below is constrained to lower and upper bounds (0 and 0.05 respectively or 0% and 5%) (see 'set_miti_bounds.gms' to prove the bounds). In this way the remaining variable on the right hand side of the equation 'v_supplementSlack(…)' takes values above zero in the case that the percentage of fat from DM is above 5%. However, in the case of taking positive values, the costs generated in part 8 of the function above are very high (through the multiplication with the factor 999999), preventing the system of using feed additives which would result in added fat shares above the 5% threshold. The slack variable is determined in the equation for SupplementPerc_ (see Figure 15).

Figure 15. Determination of the slack variable used to control the fat added with feed additives (the determination occurs in equation SupplementPerc_)

```
$iftheni.Line11 %ghgAbatement%==on
*
*        --- for the mitigation technology of feeding additional lipids from Linseed (OFLA) the maximum
*            of total fat must be below 5% of DM intake
     SupplementPerc_(RUNR,MAACT,SupplTechTot)
                              $ (CATACT(MAACT)
                              $ (p_animReq(RUNR,MAACT,"T","DRMA")*p_animProdDays(RUNR,MAACT,"T"))
                              $ p_technFact(RUNR,MAACT,"LEVL","T")
                              $ (sameas(SupplTechTot,"line_tot"))
                              $ sum((R_RAGG(RUNR,MSACT)), mitiTech_map(MSACT,MAACT,SupplTechTot,"CH4ENT")))..

*     fat in the feed bulks
          [ SUM(FEED $ (sameas(SupplTechTot,"Line_tot") $ p_maxFeedShare(RUNR,MAACT,"T",FEED)),
                v_feedInpCoeff(RUNR,MAACT,"T",FEED)
                  * sum(R_RAGG(RUNR,MSACT),p_emisFeed(RUNR,MAACT,"T",FEED,"TotFAT")))

*     fat in the feed additive lineseed added
          + p_animReq(RUNR,MAACT,"T","DRMA") * p_animProdDays(RUNR,MAACT,"T")
*           ... from max capacity
          * sum(R_RAGG(RUNR,MSACT),p_emisFeed(RUNR,MAACT,"T",SupplTechTot,"ShrOfDM"))
*          ... times actual use of this capacity (=> gives actual intake of fat from line seed)
          * v_miti(RUNR,MAACT,SupplTechTot,"CH4ENT")]

*     as a share of DM intake
      / [p_animReq(RUNR,MAACT,"T","DRMA") * p_animProdDays(RUNR,MAACT,"T")]

             =E=

*                                              Slack = excess beyond 5% (heavily penalised)
      v_supplementPerc(RUNR,MAACT,SupplTechTot) + v_supplementSlack(RUNR,MAACT,SupplTechTot);

$endif.Line11
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

3.2.3 Consideration of the mitigation costs on the equation for agricultural Income

As a further step to endogenize the mitigation measures, the total net costs of all mitigation measures together "*v_GHG_Mit_Cost_(RUNR)*" (whose calculation is shown above in Section "The net cost function of mitigation measures (the GAMS code)") are also considered in the equation for regional agricultural income (see Equation 17). Thus, when maximizing income (the agents in the regional programming models representing the European farm sector are assumed to maximize their income), the farmers also consider the costs of mitigation technologies as well as environmental policies targeting the reduction of GHG emission (i.e. subsidies or carbon taxes).

Additional to revenues and costs, the problem of income maximization is also set to several constraints (i.e. land availability, feed and fertilizer requirements and availability), which are not shown in detail here.

Equation 17. Agricultural income (regional)

$$v.obje = \sum_{RUNR} (v.linObjePart_{RUNR} - v.sumOfPmpTermsLevls_{RUNR} + v.sumOfPmpTermsFeed_{RUNR} - v.GHG.Mit.Cost_{RUNR} - v.pmpCostLandMarket_{RUNR} - v.landSupCost_{RUNR})$$

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Where:

$v.linObjePart_{RUNR}$	Gross margins (revenues - linear costs)
$v.sumOfPmpTermsLevls_{RUNR}$	Sum of pmp terms (unobserved costs) from activities
$v.sumOfPmpTermsFeed_{RUNR}$	Sum of pmp terms (unobserved costs) from feeds
$v.pmpCostLandMarket_{RUNR}$	Pmp terms (unobserved costs) from the land market
$v.GHG.Mit.Cost_{RUNR}$	Total mitigation cost which includes observed unit cost and pmp style unobserved components
$v.landSupCost_{RUNR}$	Cost for supplying land to agriculture

Note that the sum of pmp terms (unobserved costs) from feeds in the objective function above has a positive sign even though these are costs. However, the signs are partly arbitrary since once chosen, the parameter calibration is tailored to this choice. To get an interior solution the system is constrained to have negative second derivatives with respect to decision variables like activity levels and feed input coefficients. So when some activity level is increased from the optimum, the value of the objective function should decline and the same holds for feed input coefficients. The slopes of feed input coefficients have been set negative in supply\define_const_pmp_param.gms line 106. It is admitted that for the interpretation as a cost item, a negative sign would appear more natural. With a positive sign it needs to be interpreted like an unobserved revenue say from a "balanced feed mix" that is declining if feed input coefficients are increased.

4 THE EFFECT OF MITIGATION OPTIONS THAT ADDRESS THE REDUCTION OF METHANE EMISSIONS FROM ENTERIC FERMENTATION

This section presents the technical details on the modelling of endogenous mitigation measures targeting the reduction of methane emissions from enteric fermentation. Also, it presents some of the main results obtained and it shows how to get them using the Graphical User Interface (GUI). The net cost function curves are parametrized as explained in Section 3.2.2. The results presented here are those obtained with the level of the subsidy at which "full implementation" should be achieved. However, not in all cases "full implementation" or previously set upper bounds are achieved. The reasons are discussed, if applicable, in the corresponding presentation on the application of the mitigation measures below. Furthermore, each of the measures is run independently and not in combination with other measures with the purpose of isolating the effects of each of the measures.

4.1 Vaccination against methanogenic bacteria

This technological mitigation option refers to vaccines that specifically target the methane-producing methanogens in the rumen. These vaccines are still in the development phase. Nonetheless, the option is already incorporated in the CAPRI system. The technical assumptions on this option did not change in the updated GAINS (2015) compared to GAINS (2013) (cf. Höglund-Isaksson (2015)):

1. Vaccination against methanogenic bacteria reduces enteric fermentation of dairy and non-dairy cattle, as well as sheep, by 5%.
2. A cost of 10.6 euro per animal and year is assumed for this technology in the base year.

These technical assumptions are integrated in CAPRI.

Note that the vaccination measure is implemented as "end-of-pipe", meaning that only emissions (here CH4ENT) are directly affected by the measure (see Equation 10 and Figure 2).

As explained in Section 3, methane emission from enteric fermentation are calculated based on gross energy intake as calculated from the feed input coefficients for cattle or based on fixed coefficients per animal (Tier 1) for sheep. In both cases the emission factor per unit of activity (that does not consider the effect of the mitigation technologies) is multiplied with a mitigation factor (<1) which contains the information on the achieved emission savings.

The following results are obtained:

1. Figure 16 below which is based on the GUI table "Mitigation efforts" shows an implementation share of 100% (share = 1) for the vaccination measure for all single eligible activities (cattle) and the total implementation share ("share (total)") when aggregating them, using livestock units as weights. This indicates that the subsidies provided are large enough to cover the accounting and unobserved costs associated to the mitigation measure. As planned in the scenario, other mitigation measures are not implemented (even though in some cases this occurs due to simplifications in the calibration). The only measure which might be implemented without subsidies is anaerobic digestion (AD), due to the fact that it is

already applied to some extent in the reference run. This is due to the revenues obtained from it. Indeed, in the European Union, 2 % of AD is implemented without subsidies.

AD is an established technology currently implemented in some regions. Hence it is also part of the reference scenario. It generates accounting cost, pmp cost and also revenue from the energy produced. Its presence explains why the subsidies are less than 120% of the accounting cost presented in Figure 16. These accounting costs are the total accounting cost from all options implemented, which in this case are vaccination and AD. Thus, it is possible that the total accounting costs shown in this GUI table "Mitigation efforts" are higher than the subsidies (since subsidies are only given for vaccination). For example, in the European Union that is the case for dairy cows.

2. In the GUI table "mitigation efforts: details" it is possible to isolate the accounting costs and subsidies corresponding only to the vaccination measures (Figure 17). Here it can be observed that the subsidy implemented in the scenario was indeed 20% above the accounting cost, which motivates the 100% implementation rate observed in the results. The accounting costs are also reported. The assumed 10.6 € for the base year are 14.88 € in 2030 (considering an annual inflation of 1.9%) and this value is shown for dairy cows and other cows in Figure 17. For activities with a process length of less or more than 365 days the cost per head and year is converted using the process length (i.e. for HEIR: (14.88€/365)*613=24.97€/head and process length).
3. As for any other measure, we find the mitigation effects on emissions in various CAPRI GUI tables ("Environmental indicators", "Environmental indicators per activity", "Environmental indicators per activity, multiplied with activity level"). Since the vaccination is an "end of pipe" mitigation measure, the activity levels are very similar to those of a reference scenario without the implementation of the measure.

   The consequences on the level of emissions per unit of activity level are presented in Figure 18. The percentage values in the table below the absolute values give the change with respect to a reference scenario without the implementation of the measure. The change in global warming potential from agriculture (GWPA) from the aggregate "all agricultural activities" is of about 1.9%. It can be seen that change is obtained mainly from the reductions obtained from cattle activities (beef and dairy both with approx. -3.7%). Furthermore, the reduction from cattle activities are obtained from reductions on Methane emissions from enteric fermentation (approx. -5% as stated by the technical assumptions obtained from GAINS). Total methane emissions (second column in Figure 18) change approximately by -4.8% for beef and dairy activities, which is close to the -5% reduction obtained from enteric fermentation. This result is obtained since enteric fermentation is the largest source of methane with a strongly dominating share of total methane emissions. The other source of methane emissions is cattle manure management (CH4MAN). Finally, as expected, the changes obtained from "other animals" or "crops" are minimal.

Figure 16. Costs, revenues and subsidies of the mitigation measures applied and the achieved mitigation shares (scenario: subsidies granted only for vaccination)

Mitigation efforts [0]

Region: European Union — Year: 2030

res_2_1230ghg_subscal_endotech_vac

	Accounting cost of mitigation efforts [Euro /ha or head]	(Secondary) revenues from mitigation efforts [Euro /ha or head]	Pmp cost or revenue (negative) of mitigation [Euro /ha or head]	Mitigation subsidies [Euro /ha or head]	Breeding for ruminant feed efficiency [Share]	Antimethagon vaccination [Share]	Line seed as a feed additive [Share]	Nitrate as a feed additive [Share]	Anaerobic digestion based on size effects on cost [Share]
All cattle activities	22.20	2.16	-5.53	24.70	0.00	1.00	0.00	0.00	0.02
Dairy Cows high yield	18.40	5.13	-3.12	17.86		1.00	0.00	0.00	0.02
Dairy Cows low yield	18.02	4.47	-3.39	17.86		1.00	0.00	0.00	0.02
Other Cows	15.14	0.31	-4.38	17.86	0.00	1.00	0.00		0.01
Heifers breeding	25.80	0.96	-7.40	29.96		1.00	0.00	0.00	0.02
Heifers fattening high weight	17.87	0.68	-4.01	20.63	0.00	1.00		0.00	0.02
Heifers fattening low weight	9.99	0.24	-2.56	11.59	0.00	1.00		0.00	0.02
Male adult cattle high weight	15.91	0.83	-3.41	18.00	0.00	1.00		0.00	0.02
Male adult cattle low weight	8.78	0.40	-1.92	9.88	0.00	1.00		0.00	0.02
Raising male calves	14.69	0.32	-4.27	17.27	0.00	1.00			0.02
Raising female Calves	14.78	0.36	-4.28	17.34	0.00	1.00			0.02
Fattening male calves	7.64	0.17	-2.23	8.98		1.00			0.02
Fattening female calves	9.09	0.19	-2.65	10.70		1.00			0.01
Other animals	1.70	1.98	0.24						0.03
Pig fattening	0.27	0.31	0.04						0.04
Pig Breeding	0.77	0.94	0.14						0.03
Milk Ewes and Goat									
Sheep and Goat fattening	0.00		-0.00						
Laying hens									
Poultry fattening									
Other animals									
All agricultural activities	4.79	0.78	-1.10	5.01	0.00	0.20	0.00	0.00	0.01
Share (total)					0.00	1.00	0.00	0.00	0.03

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\mitigation efforts\"selection of activities and mitigation measures to be displayed in the table"

Figure 17. Isolated accounting costs and mitigation subsidies of the vaccination measure

Mitigation efforts: Details [0]

Region: European Union | Product: Antimethagon vaccination | Year: 2030

	Implementation share of mitigation option [Share]	Upper bound for implementation share of mitigation option [Share]	Accounting cost for mitigation efforts [Euro /ha or head]	(Secondary) revenue from mitigation efforts [Euro /ha or head]	Pmp cost or revenue (negative) of mitigation [Euro /ha or head]	Mitigation subsidies [Euro /ha or head]
All cattle activities	1.00	1.00	20.58		-6.17	24.70
Dairy Cows high yield	1.00	1.00	14.88		-4.46	17.86
Dairy Cows low yield	1.00	1.00	14.88		-4.46	17.86
Other Cows	1.00	1.00	14.88		-4.46	17.86
Heifers breeding	1.00	1.00	24.97		-7.49	29.96
Heifers fattening high weight	1.00	1.00	17.19		-5.16	20.63
Heifers fattening low weight	1.00	1.00	9.66		-2.90	11.59
Male adult cattle high weight	1.00	1.00	15.00		-4.50	18.00
Male adult cattle low weight	1.00	1.00	8.24		-2.47	9.88
Raising male calves	1.00	1.00	14.39		-4.32	17.27
Raising female Calves	1.00	1.00	14.45		-4.33	17.34
Fattening male calves	1.00	1.00	7.49		-2.25	8.98
Fattening female calves	1.00	1.00	8.92		-2.67	10.70
Other animals						
Pig fattening						
Pig Breeding						
Milk Ewes and Goat						
Sheep and Goat fattening						
Laying hens						
Poultry fattening						

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\mitigation efforts: details\"creation of the desired table through right mouse click on control button "pivot" in the upper right corner"

Figure 18. Consequences of the vaccination measure on the emission per unit of activity level [kg/(ha or head)]

Environmental indicators per activity [0]

Region: European Union | Year: 2030 | Scen: subscal_endotech_vac

	Global warming potential from agriculture [kg/ha or hd]	Methane output [kg/ha or hd]	Methane emissions from enteric fermentation (IPCC) [kg/ha or hd]	Methane emissions from manure management (IPCC) [kg/ha or hd]	Methane emissions from rice production (IPCC) [kg/ha or hd]	N2O output [kg/ha or hd]	Ammonia output [kg/ha or hd]
Utilized agricultural area	687.65 -0.07%	0.39 -0.00%			0.39 -0.00%	2.28 -0.07%	3.27 -0.06%
Cereals	831.19 -0.08%	1.23 0.04%			1.23 0.04%	2.69 -0.08%	5.79 -0.04%
Oilseeds	902.84 -0.05%					3.03 -0.05%	5.71 -0.02%
Other arable crops	970.37 -0.06%					3.26 -0.06%	4.74 -0.02%
All cattle activities	3698.56 -3.71%	113.09 -4.74%	103.38 -5.12%	9.71 -0.44%		2.92 -0.20%	17.56 -0.10%
Beef meat activities	3182.09 -3.67%	94.65 -4.84%	89.73 -5.06%	4.92 -0.61%		2.74 -0.10%	13.96 -0.06%
All Dairy	3947.75 -3.71%	121.99 -4.68%	109.96 -5.13%	12.03 -0.37%		3.01 -0.24%	19.30 -0.10%
Other animals	1623.07 -0.46%	33.27 -0.42%	18.69 -0.05%	14.58 -0.88%		2.66 -0.51%	18.97 0.01%
All agricultural activities	1457.98 -1.93%	28.86 -3.66%	24.16 -4.23%	4.46 -0.61%	0.24 -0.07%	2.47 -0.17%	8.84 0.02%

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\environmental indicators per activity\"selection of activities and mitigation measures to be displayed in the table"

4.2 Feed additives: nitrate

Using nitrate as a feed additive can reduce methane emissions from enteric fermentation. The methane reduction potential is high, but it requires a careful dosage to avoid negative health effects.

For example, Latham et al (2016)[6] state that further studies are needed to more clearly define benefits and risks of using nitrate as supplements to cattle diets.

Following the approach from the AnimalChange Project[7], it is assumed that feeding of nitrate can be applied to 100% of dairy cows and to 50% of fattening cattle and heifers (for the time they spend in the stable). Also, it is assumed that for dairy cows adding nitrate to the feed is limited to the time of lactation (10 months/year). These assumptions are coded as constraints to the implementation share which result in upper limits < 1 (see capri\gams\envind\ line_nitr.gms). Furthermore, the intake of nitrate is limited to a maximum of 1.5% of total dry matter intake. For each percentage of nitrate added, methane emissions from enteric fermentation are assumed to decline by 10%. Thus, the maximum reduction possible is 15%. Furthermore, as dietary nitrate increases the excretion of N, an equivalent reduction of the intake of crude protein (content of nitrogen in the feed) of 0.42% for 1.5% nitrate is assumed (Mottet et al. 2015).

The cost information is based on the price of the feed additive "Bolifor" divided by its share of nitrates (see Figure 19). This estimate is subsequently reduced by half to acknowledge (in a rough way) that there should be cost savings as well from reduced protein requirements and energy losses via methane.

Figure 19. Code showing that the price of nitrate is based on the feed additive "Bolifor"

```
*--- Price of nitrate (Bolifor CNF: 550 EUR/ton, share of nitrate in BOLIFOR is 63% ==> 873=550/0.63)
   p_ghgMiti(ms_LiNi,PACT,"Nitr_Tot","CH4ENT","costParLin") $ mitiTech_map(ms_LiNi,PACT,"nitr_Tot","CH4ENT")
    = 873*p_inflationFactor(ms_LiNi) $ p_ghgMiti(ms_LiNi,PACT,"nitr_tot","CH4ENT","MaxShare") ;
```

Location in CAPRI file structure: '…CapriTrunk\gams\envind\line_nitr.gms'

The nitrogen content is considered in the feed protein constraint which is controlled through the set "REQMSE" (components of the set are: (i) ENNE – net energy for lactation and (ii) CRPR – crude protein) in the equation "REQSE_" (requirement of animals written as equality) below (see Figure 20). The nitrates enter the balance as a source of nitrogen just as the other feedstuffs.

The cost savings of this mitigation measure (due to less protein requirements in feed) are considered in the calibration approach (parametrization of the mitigation cost curve) (see Subsection (iii) from Section 3.2.2.)

[6] Latham et al (2016), Insights on Alterations to the Rumen Ecosystem by Nitrate and Nitrocompounds, Front Microbiol.; 7: 228. Doi: 10.3389/fmicb.2016.00228

[7] http://www.animalchange.eu/

Figure 20. Requirements (energy and protein) of animals written as equalities (incomplete presentation of the equation)

```
*         --- constraint that requirement of animals must be covered by feeding
*             equality restrictions (energy, protein)
*
     REQSE_(RUNR,MAACT,A,REQMSE) $ (  p_animReq(RUNR,MAACT,A,REQMSE) $ p_technFact(RUNR,MAACT,"LEVL",A) ) ..
*
*                                --- animal requirements per activity level and day
         (v_animReq(RUNR,MAACT,A,REQMSE)  $ p_trimFeed + p_animReq(RUNR,MAACT,A,REQMSE) $ (Not p_trimFeed))

$iftheni.lnf6 %ghgAbatement%==on
*                                    -- considering a possible modification by mitigation option lowNFeed
              * (1 + v_Miti(RUNR,MAACT,"lowNFeed","N2OEXCR")*p_ghgMiti(RUNR,MAACT,"lowNFeed","othImpact","CRPR") $ SAMEAS(REQMSE,"CRPR"))
*                                    -- consider a reduction of energy need by option genet_eff:
              * (1 + v_Miti(RUNR,MAACT,"genet_eff","rumFedEff")*p_ghgMiti(RUNR,MAACT,"genet_eff","othImpact",REQMSE) )
*                                    -- consider a modification by mitigation option mlkYld
              * (1 + v_Miti(RUNR,MAACT,"genet_yld","mlkYld")*p_ghgMiti(RUNR,MAACT,"genet_yld","othImpact",REQMSE) $ PACT_TO_Y(MAACT,"COMI"))
$endif.lnf6
              * p_animProdDays(RUNR,MAACT,A)
*                                --- are covered by feeding of feedingstuff
             -  SUM(FEED $ p_maxFeedShare(RUNR,MAACT,A,FEED),
                      v_feedInpCoeff(RUNR,MAACT,A,FEED)
                         * SUM(R_RAGG(RUNR,MSACT),%data%(MSACT,REQMSE,FEED,"Y")))

$iftheni.Lin1 %ghgAbatement%==on
*           Protein saving through feed additive nitrates
            - p_animReq(RUNR,MAACT,A,"DRMA") * p_animProdDays(RUNR,MAACT,A)
                    * v_miti(RUNR,MAACT,"Nitr_tot","CH4ENT")*p_emisFeed(RUNR,MAACT,"T","Nitr_tot","CRPR")
                    $ (SAMEAS(REQMSE,"CRPR") $ (CATACT(MAACT)
                        $ sum(R_RAGG(RUNR,MSACT), mitiTech_map(MSACT,MAACT,"Nitr_tot","CH4ENT"))))
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Note 1: not all the equation is presented in the figure.

Note 2: "REQSE_" is an equation defining the requirement of animals written as equality.

Note 3: "REQMSE" is a set whose components are: (i) ENNE – net energy for lactation and (ii) CRPR – crude protein.

Note 4: "p_emisFeed(RUNR,MAACT,"T","Nitr_tot","CRPR")" is the coefficient stating the maximum intake of nitrate as a share from dry matter (0.015 or 1.5% as stated in the text above).

We obtain the following results:

1. From Figure 21: the aggregate implementation share ('share (total)', weighted average over all eligible activities) in the EU is of 36%.
2. We also observe small implementation shares for the measure "breeding for ruminant feed efficiency" when the application of nitrates is subsidized. This is because the calibration approach represented by equation 13 neglects interrelationships between different mitigation measures. In the full supply model these may be significant, in particular in the feed sector such that inaccuracies, often also quite large, occur for those measures interlinked with others.
3. The "Mitigation efforts: details" table (Figure 22) permits to check if a certain implementation share is constrained by an upper bound < 1 (see again capri\gams\envind\line_nitr.gms). The table shows that, indeed, for nitrate as a feed additive, an upper bound constrains the maximum implementation share possible. This explains why, even though the subsidies are only given for this measure, the implementation shares are below 1 (or 100%). However, note that the mitigation option is not applied fully up to the upper bound. This is due to: (i) interrelationships with other measures like 'breeding for ruminant feed efficiency' (implemented with small but not entirely zero shares –a total share of 4% in the European

Union–) or (ii) due to a strong decline in the cost savings when moving from the initial to the maximum implementation share (as explained in the Subsection (iii) from Section 3.2.2.).

In Figure 22 it can also be seen that the mitigation subsidies are 120% from the accounting costs, indicating that nitrate as a feed additive is treated as a new technology (not implemented in the base year).

4. The improvement in GHG emissions are presented in Figure 23. The overall effect on global warming potential from agriculture (GWPA) is of 1.7%. The improvement for total methane emissions is of 3.2% and for CH4ENT alone of 3.8%. Note that the columns 'total' and 'impact in GWP' are not equal since totals are in CH4/N2O emissions and 'impact in GWP' in CO2 equivalents.

Figure 21. Costs, revenues and subsidies of the mitigation measures applied and the achieved mitigation shares (scenario: subsidies granted only to nitrate as a feed additive)

Mitigation efforts [0]

Region: European Union — Year: 2030

	Accounting cost of mitigation efforts [Euro /ha or head]	(Secondary) revenues from mitigation efforts [Euro /ha or head]	Pmp cost or revenue (negative) of mitigation [Euro /ha or head]	Mitigation subsidies [Euro /ha or head]	Breeding for ruminant feed efficiency [Share]	Antimethagon vaccination [Share]	Line seed as a feed additive [Share]	Nitrate as a feed additive [Share]	Anaerobic digestion based on size effects on cost [Share]
All cattle activities	16.62	2.16	64.98	16.20	0.02		0.00	0.25	0.02
Dairy Cows high yield	44.53	5.13	164.94	42.55			0.00	0.50	0.02
Dairy Cows low yield	32.94	4.47	124.74	32.81			0.00	0.47	0.02
Other Cows	0.33	0.31	1.58		0.01		0.00		0.01
Heifers breeding	9.44	0.98	38.03	10.30				0.25	0.02
Heifers fattening high weight	9.02	0.69	53.22	9.27	0.12			0.21	0.03
Heifers fattening low weight	4.21	0.24	24.45	4.44	0.12			0.22	0.02
Male adult cattle high weight	7.78	0.84	44.14	7.77	0.11			0.22	0.02
Male adult cattle low weight	4.19	0.41	23.66	4.18	0.11			0.23	0.02
Raising male calves	0.31	0.32	0.26		0.00				0.02
Raising female Calves	0.35	0.37	0.38		0.01				0.02
Fattening male calves	1.14	0.17	4.63	1.17	0.01			0.19	0.02
Fattening female calves	1.83	0.19	8.61	1.92	0.02			0.21	0.01
Other animals	1.70	1.98	0.24		0.00				0.03
Pig fattening	0.27	0.31	0.04						0.04
Pig Breeding	0.77	0.94	0.14						0.03
Milk Ewes and Goat									
Sheep and Goat fattening	0.00		0.00		0.00				
Laying hens									
Poultry fattening									
All agricultural activities	3.66	0.78	13.23	3.29	0.00		0.00	0.05	0.01
Share (total)					0.04		0.00	0.36	0.03

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\mitigation efforts\"selection of activities and mitigation measures to be displayed in the table"

Figure 22. Isolated details for the mitigation technology 'nitrate as feed additive'

Mitigation efforts: Details [0]

Region: European Union | Product: nitrate as a feed additive

res_2_1230ghg_subscal_endotech_nitr

	Implementation share of mitigation option [Share]	Upper bound for implementation share of mitigation option [Share]	Accounting cost for mitigation efforts [Euro /ha or head]	(Secondary) revenue from mitigation efforts [Euro /ha or head]	Pmp cost or revenue (negative) of mitigation [Euro /ha or head]	Mitigation subsidies [Euro /ha or head]
All cattle activities	0.25	0.29	13.50		59.32	16.20
Dairy Cows high yield	0.50	0.56	35.46		154.17	42.55
Dairy Cows low yield	0.47	0.56	27.34		119.24	32.81
Other Cows						
Heifers breeding	0.25	0.28	8.59		37.94	10.30
Heifers fattening high weight	0.21	0.27	7.72		37.44	9.27
Heifers fattening low weight	0.22	0.27	3.70		18.14	4.44
Male adult cattle high weight	0.22	0.29	6.48		30.41	7.77
Male adult cattle low weight	0.23	0.29	3.49		16.51	4.18
Raising male calves						
Raising female Calves						
Fattening male calves	0.19	0.25	0.97		4.37	1.17
Fattening female calves	0.21	0.27	1.60		7.60	1.92
Other animals						
Pig fattening						
Pig Breeding						
Milk Ewes and Goat						
Sheep and Goat fattening						
Laying hens						
Poultry fattening						
All agricultural activities	0.05	0.06	2.74		12.05	3.29

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\mitigation efforts: details\"creation of the desired table through right mouse click on control button "pivot" in the upper right corner"

Figure 23. Consequences of the mitigation measure 'nitrate as feed additive' on the emissions of different GHG types

Environmental indicators [0]

Region: European Union | Year: 2030 | Scen: subscal_endotech_nitr | Percentage diff. to Scen refpol_endotech_noc_sup | View type: Table

	Total [in 1000t]	Amount per ha [in 1000t/ha]	Impact in GWP [in 1000t CO2 eq]
Ammonium output	2540.53 0.31%		
CH4 Total emissions	8307.01 -3.18%	46.24 -3.18%	207675.34 -3.18%
Emissions of CH4ENT	6954.23 -3.77%	38.71 -3.77%	173855.62 -3.77%
Emissions of CH4MAN	1283.29 -0.07%	7.14 -0.07%	32082.29 -0.07%
Emissions of CH4RIC	69.50 0.00%	0.39 -0.00%	1737.43 0.00%
N2O Total emissions	707.77 -0.19%	3.94 -0.19%	210914.39 -0.19%
Global warming potential from agriculture			418589.75 -1.70%

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\environmental indicators\"selection of activities and mitigation measures to be displayed in the table"

4.3 Feed additives: linseed

Supplementing animal diets with lipids (vegetable oils or animal fat) is used to increase the energy content of the diet and to enhance energy utilization (i.e. it impacts dry matter intake and digestibility). The combination of decreased dry matter intake and (potentially) maintained or increased production improves feed efficiency and results in decreased methane emissions from cattle. One of the most efficient dietary lipids is linseed. However, the effectiveness of feeding linseed in decreasing enteric methane emissions depends on the feed mix. Furthermore, feeding too much linseed can have negative effects on the overall diet digestibility.

As in the case of nitrate as feed additive, for linseed we also follow the assumptions made in the AnimalChange Project[8], namely that this mitigation option can be applied to 100% of dairy cows, but only to 50% of other cattle categories as the intake has to be constant which 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 from region to region. It is assumed that for each percent of fat added, a 5% reduction of methane emissions from enteric fermentation is achieved (Mottet et al. 2015).

The cost information is adopted from the literature on feeding strategies for dairy farming (see Figure 24).

Figure 24. Code showing the calculations to get the price of linseed

```
*--- Price of line seed (no supplementary costs are considered) are from:
*    van Middelaar,C.E. et al (2014), Cost-effectiveness of feeding strategies to reduce GHG emissions from dairy farming,
*    J.of Dairy Sciences, Vol.97, pp.2427-2439, Table 2.
*    40.5 is the fat content of rape (supposed to be similar to line seed), 89.9 is the DM share
*    => result is Euro/tFM * tDM/tFM / (tFat/tDM) = Euro/tFat so Euros per ton of fat
   p_ghgMiti(ms_LiNi,PACT,"LINE_Tot","CH4ENT","costParLin") $ mitiTech_map(ms_LiNi,PACT,"LINE_Tot","CH4ENT")
    = (674 * 89.9 / 40.5)*p_inflationFactor(ms_LiNi) $ p_ghgMiti(ms_LiNi,PACT,"Line_tot","CH4ENT","MaxShare")
 ;
```

Location in CAPRI file structure: '…CapriTrunk\gams\envind\line_nitr.gms'

This estimate is subsequently reduced by half to acknowledge (at least in a rough way) that there are cost savings, in the same way as in the case of nitrates as a fed additive, for example from lower energy requirements to be covered from other feed.

The content of linseed in terms of energy is considered in the feed requirement functions. The first parts of this equation (reqse_) has been already presented (Figure 20). The analysis of the complete equation (Figure 25) reveals that mitigation measures might modify the feed restrictions in many ways.

[8] http://www.animalchange.eu/

Figure 25. Requirements (energy and protein) of animals written as equalities (complete presentation of the equation)

```
*         --- constraint that requirement of animals must be covered by feeding
*             equality restrictions (energy, protein)
*
     REQSE_(RUNR,MAACT,A,REQMSE) $ (  p_animReq(RUNR,MAACT,A,REQMSE) $ p_technFact(RUNR,MAACT,"LEVL",A) ) ..
*
*                                  --- animal requirements per activity level and day
         (v_animReq(RUNR,MAACT,A,REQMSE)  $ p_trimFeed + p_animReq(RUNR,MAACT,A,REQMSE) $ (Not p_trimFeed))

$iftheni.lnf6 %ghgAbatement%==on
*                                    -- considering a possible modification by mitigation option lowNFeed
              * (1 + v_Miti(RUNR,MAACT,"lowNFeed","N2OEXCR")*p_ghgMiti(RUNR,MAACT,"lowNFeed","othImpact","CRPR") $ SAMEAS(REQMSE,"CRPR"))
*                                    -- consider a reduction of energy need by option genet_eff:
              * (1 + v_Miti(RUNR,MAACT,"genet_eff","rumFedEff")*p_ghgMiti(RUNR,MAACT,"genet_eff","othImpact",REQMSE) )
*                                    -- consider a modification by mitigation option mlkYld
              * (1 + v_Miti(RUNR,MAACT,"genet_yld","mlkYld")*p_ghgMiti(RUNR,MAACT,"genet_yld","othImpact",REQMSE) $ PACT_TO_Y(MAACT,"COMI"))
$endif.lnf6
              * p_animProdDays(RUNR,MAACT,A)
*                                  --- are covered by feeding of feedingstuff
             -  SUM(FEED $ p_maxFeedShare(RUNR,MAACT,A,FEED),
                     v_feedInpCoeff(RUNR,MAACT,A,FEED)
                        * SUM(R_RAGG(RUNR,MSACT),%data%(MSACT,REQMSE,FEED,"Y")))

$iftheni.Lin1 %ghgAbatement%==on
*           Protein saving through feed additive nitrates
            - p_animReq(RUNR,MAACT,A,"DRMA") * p_animProdDays(RUNR,MAACT,A)
                    * v_miti(RUNR,MAACT,"Nitr_tot","CH4ENT")*p_emisFeed(RUNR,MAACT,"T","Nitr_tot","CRPR")
                    $ (SAMEAS(REQMSE,"CRPR") $ (CATACT(MAACT)
                        $ sum(R_RAGG(RUNR,MSACT), mitiTech_map(MSACT,MAACT,"Nitr_tot","CH4ENT"))))


*           Nutrients from Lineseed
            - ( p_animReq(RUNR,MAACT,A,"DRMA") * p_animProdDays(RUNR,MAACT,A)
*           ... times maximum % of DM from line seed fat (=5%)
              * sum(R_RAGG(RUNR,MSACT) $ (CATACT(MAACT) $ mitiTech_map(MSACT,MAACT,"Line_tot","CH4ENT")),
                p_emisFeed(RUNR,MAACT,"T","Line_tot","ShrOfDM")
*           ... times actual use (0<=v_miti<=1) of this maximum capacity (=> gives actual intake of fat from line seed)
              * v_miti(RUNR,MAACT,"Line_tot","CH4ENT")
*           ... divided by fat content of line seed (=> gives actual intake of fresh matter from line seed)
              / p_emisFeed(RUNR,MAACT,"T","Line_tot","TotFAT")
*           ... times REQMSE-content (=> gives actual intake of REQMSE from line seed that has to be deducted)
              * p_emisFeed(RUNR,MAACT,"T","Line_tot",REQMSE)) ) $ (  p_emisFeed(RUNR,MAACT,"T","Line_tot","TotFAT")
                                                                  $ p_emisFeed(RUNR,MAACT,"T","Line_tot",REQMSE) )
$endif.Lin1
*
               =E= 0.0;
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Note 1: "REQSE_" is an equation defining the requirement of animals written as equality.
Note 2: "REQMSE" is a set whose components are: (i) ENNE – net energy for lactation and (ii) CRPR – crude protein.

The case of linseed presents the additional difficulty of ensuring that total fat intake does not exceed 5% of dry matter, including the fat from other feedstuffs. How this is modelled in CAPRI is shown is explained in Figure 14 and Figure 15 in Section 3.2.2.

Also note that linseed can be an additive alone or that its application can be combined with the simultaneous application of nitrate. For this reason, it is necessary that the code is able to distinguish between the single ('Line', 'Nitr') and combined application ('AComLN') as well as the total. Thus, apart from the single options, new positions are created ('line_tot' = line + AComLN and 'nitr_tot' = Nitr + AComLN) which capture the total applications of those supplements (see Figure 26).

Figure 26. Computation of total application of feed additives linseed and nitrates from pure and combined application

```
* --- Total application of feed additives lineseed or nitrates from pure and combined application
   Tot_LineNitr_(RUNR,PACT,SupplTechTot,mitiTarget) $ sum((R_RAGG(RUNR,MSACT),mitiTech_map(MSACT,PACT,SupplTechTot,mitiTarget)),1)..
      v_Miti(RUNR,PACT,SupplTechTot,mitiTarget)
    =e= sum(SupplTech_TotMap(SupplTechTot,SupplTechNotTot) $ sum(R_RAGG(RUNR,MSACT),mitiTech_map(MSACT,PACT,SupplTechNotTot,mitiTarget)),
      v_Miti(RUNR,PACT,SupplTechNotTot,mitiTarget));
```

Location in CAPRI file structure: '…CapriTrunk\gams\supply\supply_model.gms'

Note 1: 'v_miti': implementation shares of the mitigation measures.

Note 2: 'SupplTechTot': supplement type mitigation technologies (only totals: line_tot and nitr_tot)
Note 3: 'SupplTechNotTot': supplement type mitigation technologies (only single applications: line, nitr, AComLN)

Now, when analyzing the results of the test scenario in which subsidies are only granted to linseed, we get the following:

1. From Figure 27: An overall mitigation share of 24% with the highest being those of the dairy cows.
2. From Figure 28: That it is mostly the upper bounds that explain the moderate implementation shares of the measure (as for the previous measure nitrate), although the upper bounds are not fully reached. In addition to the explanations offered for other measures (interrelationships with other measures or strong decline in the cost savings when moving to the maximum implementation) the binding 5% fat constraint might also prevent the simulated shares to fully attain the upper limits in certain regions. Note also that the subsidy rate is of 120% of the accounting cost (as for nitrate) when looking at the isolated details of the mitigation technology. This is the assumed level of the subsidy at which "full implementation" is achieved (see Subsection (i) from Section 3.2.2).
3. From Figure 29: The improvement in overall GHG emissions is of 2.8%, for total methane emissions of 5.6% and for methane from enteric fermentation (CH4ENT) alone of 6.7%. Note that the methane emissions from manure management increase by 0.5%, suggesting that there might be also an increase in activity levels.
4. From Figure 30: Indeed, a look into the supply details reveals that there is an increase in cattle activities (increase in all cattle activities of 1.8%). Apparently the combination of subsidies and feed cost savings provides sizeable incentives for an expansion of activity levels.

Figure 27. Costs, revenues and subsidies of the mitigation measures applied and the achieved mitigation shares (scenario: subsidies granted only to linseed as a feed additive)

Mitigation efforts [0]

Region: European Union

Year: 2030

res_2_1230ghg_subscal_endotech_line

	Accounting cost of mitigation efforts [Euro /ha or head]	(Secondary) revenues from mitigation efforts [Euro /ha or head]	Pmp cost or revenue (negative) of mitigation [Euro /ha or head]	Mitigation subsidies [Euro /ha or head]	Breeding for ruminant feed efficiency [Share]	Antimethag on vaccination [Share]	Line seed as a feed additive [Share]	Nitrate as a feed additive [Share]	Anaerobic digestion based on size effects on cost [Share]
All cattle activities	71.88	2.15	88.07	82.78	0.01		0.24	0.00	0.02
Dairy Cows high yield	129.06	5.12	155.52	144.87			0.31	0.00	0.02
Dairy Cows low yield	109.34	4.46	129.32	124.81			0.32	0.00	0.02
Other Cows	36.41	0.32	46.00	43.26	0.02		0.17		0.01
Heifers breeding	77.22	1.00	88.51	91.62			0.25		0.02
Heifers fattening high weight	48.71	0.69	69.47	57.35	0.05		0.24		0.03
Heifers fattening low weight	23.40	0.24	33.41	27.69	0.02		0.24		0.02
Male adult cattle high weight	28.80	0.84	40.20	33.36	0.03		0.14		0.02
Male adult cattle low weight	20.23	0.41	27.76	23.61	0.04		0.22		0.02
Raising male calves	13.87	0.33	19.66	16.18	0.04		0.19		0.02
Raising female Calves	13.64	0.37	18.19	15.89	0.03		0.20		0.02
Fattening male calves	5.03	0.17	6.44	5.85	0.00		0.12	0.00	0.02
Fattening female calves	7.52	0.19	10.29	8.82	0.00		0.14	0.00	0.01
Other animals	1.69	1.98	0.24		0.00				0.03
All agricultural activities	15.07	0.78	18.14	17.02	0.00		0.05	0.00	0.01
Share (total)					0.03		0.24	0.00	0.03

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\mitigation efforts\"selection of activities and mitigation measures to be displayed in the table"

Figure 28. Isolated details for the mitigation technology 'linseed as feed additive'

Mitigation efforts: Details [0]

Region: European Union | Product: line seed as a feed additive | Year: 2030

	Implementation share of mitigation option [Share]	Upper bound for implementation share of mitigation option [Share]	Accounting cost for mitigation efforts [Euro /ha or head]	(Secondary) revenue from mitigation efforts [Euro /ha or head]	Pmp cost or revenue (negative) of mitigation [Euro /ha or head]	Mitigation subsidies [Euro /ha or head]
All cattle activities	0.24	0.26	68.98		82.87	82.78
Dairy Cows high yield	0.31	0.32	120.72		142.46	144.87
Dairy Cows low yield	0.32	0.34	104.01		123.36	124.81
Other Cows	0.17	0.21	36.05		43.90	43.26
Heifers breeding	0.25	0.28	76.35		88.41	91.62
Heifers fattening high weight	0.24	0.25	47.79		63.11	57.35
Heifers fattening low weight	0.24	0.26	23.08		31.92	27.69
Male adult cattle high weight	0.14	0.16	27.80		34.71	33.36
Male adult cattle low weight	0.22	0.23	19.67		24.71	23.61
Raising male calves	0.19	0.22	13.48		17.86	16.18
Raising female Calves	0.20	0.22	13.24		16.95	15.89
Fattening male calves	0.12	0.13	4.88		6.42	5.85
Fattening female calves	0.14	0.15	7.35		10.24	8.82
Other animals						
All agricultural activities	0.05	0.05	14.19		17.04	17.02

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\mitigation efforts: details\"creation of the desired table through right mouse click on control button "pivot" in the upper right corner"

Figure 29. Consequences of the mitigation measure 'linseed as feed additive' on the emissions of different GHG types

Environmental indicators [0]

Region: European Union | Year: 2030 | Scen: subscal_endotech_line | Percentage diff. to Scen refpol_endotech_noc_sup | View type: Table

	Total [in 1000t]	Amount per ha [in 1000t/ha]	Impact in GWP [in 1000t CO2 eq]
Ammonium output	2549.64 0.67%		
CH4 Total emissions	8103.29 -5.56%	45.11 -5.56%	202582.20 -5.56%
Emissions of CH4ENT	6743.00 -6.69%	37.54 -6.69%	168574.89 -6.69%
Emissions of CH4MAN	1290.78 0.51%	7.19 0.51%	32269.53 0.51%
Emissions of CH4RIC	69.51 0.02%	0.39 0.02%	1737.79 0.02%
N2O Total emissions	709.01 -0.01%	3.95 -0.01%	211284.17 -0.01%
Global warming potential from agriculture			413866.38 -2.80%

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\environmental indicators\"selection of activities and mitigation measures to be displayed in the table"

Figure 30. Supply details

	Supply [1000 t, 1000 ha or Mio Const EU]
All cattle activities	103938.06 1.77%
Dairy Cows high yield	108736.01 1.69%
Dairy Cows low yield	64585.54 1.57%
Other Cows	5589.23 3.84%
Heifers breeding	8149.57 4.09%
Heifers fattening high weight	728.81 1.85%
Heifers fattening low weight	477.90 1.27%
Male adult cattle high weight	1897.67 1.18%
Male adult cattle low weight	1254.21 1.36%
Raising male calves	8780.54 1.51%
Raising female Calves	11724.45 1.64%
Fattening male calves	817.47 0.42%
Fattening female calves	370.70 0.47%
Beef meat activities	17666.12 1.47%
Other animals	91806.25 -0.13%
All agricultural activities	435767.25 0.40%

4.4 Breeding for increased feed efficiency

A promising GHG mitigation option could be a breeding program which increases ruminant feed efficiency. We assume that the main effects (at a 100% implementation) are:

1. A 10% reduction in energy need of non-dairy ruminants. This value is based on the recent literature review by the GAINS team (Höglund-Isaksson 2015).
2. A 5% reduction in crude protein need. This is assumed for two reasons:
    a. Such decrease in crude protein need goes along with the reduction on energy needs.
    b. In test runs we see that an exclusive reduction of energy need by 10% creates strong incentives for changes in the feed mix towards protein rich feed. This appears implausible and in some cases even infeasible, in particular in regions that strongly rely on grass.

Reduced feed intake caused by higher feed efficiency leads to lower methane emissions of cattle activities since the calculation in CAPRI is based on the energy intake (Tier 2, see Section 3). For sheep (Tier 1 in CAPRI) we include a special reduction factor that also reduces methane from enteric fermentation by 10% if the measure is fully implemented. The different technical treatment is necessary since the accounting for sheep is simpler, however, the main effect (10% savings) is the same. It is also assumed that the breeding program focuses on non-dairy ruminants. This because the dairy cows and breeding heifers are targeted by an alternative breeding program improving milk yields.

How is this measure implemented? The gams file 'breeding.gms' defines its technical effects and costs. The impacts on requirements are collected as percentages. These are saved in a parameter 'p_ghgMiti' used to specify different mitigation information (see Figure 31).

Figure 31. Implementation of the 10% and 5% impact on energy and protein savings

```
* --- Technical effecs of breeding for higher feed efficiency of non-dairy ruminants
*     Note: This is meant to target enteric fermentation => the main impact should be on energy savings
*
  p_ghgMiti(RU,MPACT,"genet_eff","othImpact","ENNE") $ p_ghgMiti(RU,MPACT,"genet_eff","rumFedEff","maxShare")
    = - p_ghgTechFEff ;

*     -- but an exclusive change on energy may cause an imbalance in metabolism.
*        So we assume that CRPR declines half as much as energy:

  p_ghgMiti(RU,MPACT,"genet_eff","othImpact","CRPR") $ p_ghgMiti(RU,MPACT,"genet_eff","rumFedEff","maxShare")
    = .5 * p_ghgMiti(RU,MPACT,"genet_eff","othImpact","ENNE") ;
```

Location in CAPRI file structure: '…CapriTrunk\gams\envind\breeding.gms'

Note 1: 'p_ghgMiti': parameter to specify the mitigation effect defined in 'RU' (the regional units in the current run), 'MPACT' (production activities), 'genet_eff' (the mitigation measure 'breeding for increased feed eff.'), 'othImpact' (impacts on variables other than the direct targets), 'ENNE' (net energy), and 'CRPR' (crude protein).

Note 2: 'p_ghgTechFEff' = 0.1 (scalar capturing the technical effect of 10%)

The accounting costs are assumed to be 5% of the estimated savings in feed costs; however, with the restriction that these must at least be 2 Euros per animal. The savings in feed costs are estimated as the percentage reduction in energy requirements times the value of feed use in the reference run.

Figure 32. Estimate of the accounting costs of the mitigation measure 'breeding for increased feed efficiency'

```
*     -- Estimate accounting cost of breeding program for feed efficiency as x% of potential savings in feed cost if the
*        value of feed would just derive from energy. Note that net benefits will be calibrated to be zero.

   p_ghgMiti(RU,MAACT,"genet_eff","rumFedEff","costParLin") $ (   SUM(RU_MS(RU,MS),DATA(MS,MAACT,"DAYS","Y"))
                                                              $ p_ghgMiti(RU,MAACT,"genet_eff","rumFedEff","maxShare"))
      = max(2,0.05* SUM(FEED,DATA(RU,MAACT,FEED,"Y")*SUM(RU_MS(RU,MS),DATA(MS,"UVAG",FEED,"Y")
                                                                  /  (DATA(MS,MAACT,"DAYS","Y")/365)))*0.001
                   * (-p_ghgMiti(RU,MAACT,"genet_eff","othImpact","ENNE")))
   ;
```

Location in CAPRI file structure: '…CapriTrunk\gams\envind\breeding.gms'

Note 1: 'p_ghgMiti'(RU,MAACT,"genet_eff","rumFedEff","costParLin": parameter to specify the accounting costs. Defined in 'RU' (the regional units in the current run), 'MAACT' (animal production activities), 'genet_eff' (the mitigation measure 'breeding for increased feed eff.'), 'rumFedEff' (target variable for measure 'higher feed efficiency of non-dairy ruminants'), 'costParLin' (accounting costs).

Note 2: 'UVAG': Unit value EAA gross producer price

Note 3: p_ghgMiti(RU,MAACT,"genet_eff","othImpact","ENNE"): parameter specifying the percentage reduction in energy requirements. Its value is -0.10 according to current assumptions.

The parameter specification of the net cost function is done based on the case when the mitigation technology is not adopted in the base year (see Section 3.2.2). Thus, the subsidy rate needed for full implementation is assumed to be 120% of the accounting cost and the entry subsidies are set to 10%.

We obtain the following results:

1. From Figure 33: The resulting aggregate implementation share (line "share (total)") is 40%.
2. From Figure 34: The implementation shares are significantly lower than the upper bounds. Apparently the measure is affected more than usually by calibration problems. A particularity of the measure is that the accounting costs are relatively low. As the subsidies are set to 120% of the accounting cost in the full implementation case, this is only a moderate incentive compared to large unobserved cost (see accounting and pmp costs in Figure 34). This might be an explanation for the behavior. However, these particular calibration problems will be revisited.
3. From Figure 35: The improvement in overall GHG emissions is of 0.66%, for total methane emissions of 0.95% and for methane from enteric fermentation (CH4ENT) alone of 1.05%. These emission savings appear to be modest. However, remember that the implementation is limited to the non-dairy cattle and sheep and goats and that the implementation share is not high (17% in 'all cattle activities'). Also, improvements from 0.37% are achieved for N2O. This occurs since the reductions in crude protein intake cause N in excretions to decline which reduces N related emissions.
4. From Figure 36: A detailed look to the methane emissions from ruminants shows that the measure cannot have a big impact. A large share of methane from enteric fermentation is not covered by the measure (i.e. dairy cows, heifers breeding and milk ewes and goats).

Figure 33. Costs, revenues and subsidies of the mitigation measures applied and the achieved mitigation shares (scenario: breeding for increased feed efficiency)

Mitigation efforts [0]

Region: European Union | Year: 2030

	Accounting cost of mitigation efforts [Euro /ha or head]	(Secondary) revenues from mitigation efforts [Euro /ha or head]	Pmp cost or revenue (negative) of mitigation [Euro /ha or head]	Mitigation subsidies [Euro /ha or head]	Breeding for ruminant feed efficiency [Share]	Antimethag on vaccination [Share]	Line seed as a feed additive [Share]	Nitrate as a feed additive [Share]	Anaerobic digestion based on size effects on cost [Share]
All cattle activities	2.85	2.16	21.52	1.41	0.17		0.00	0.00	0.02
Dairy Cows high yield	3.56	5.14	1.46				0.00	0.00	0.02
Dairy Cows low yield	3.16	4.48	1.14				0.00	0.00	0.02
Other Cows	1.63	0.31	28.80	1.64	0.27		0.00		0.01
Heifers breeding	0.86	0.96	0.17					0.00	0.02
Heifers fattening high weight	2.54	0.68	32.43	2.01	0.25			0.01	0.02
Heifers fattening low weight	1.57	0.24	19.19	1.27	0.34			0.02	0.02
Male adult cattle high weight	2.61	0.83	30.13	1.83	0.26			0.01	0.02
Male adult cattle low weight	1.66	0.40	18.34	1.21	0.33			0.01	0.02
Raising male calves	1.62	0.32	21.54	1.59	0.46				0.02
Raising female Calves	1.47	0.36	19.32	1.36	0.43				0.02
Fattening male calves	1.43	0.17	16.51	1.49	0.69		0.00	0.01	0.02
Fattening female calves	1.85	0.19	21.41	1.96	0.63			0.01	0.01
Other animals	2.76	1.98	2.81	1.27	0.05				0.03
Pig fattening	0.27	0.31	0.04						0.04
Pig Breeding	0.77	0.94	0.14						0.03
Milk Ewes and Goat									
Sheep and Goat fattening	1.07		2.61	1.29	0.97				
Laying hens									
Poultry fattening									
All agricultural activities	1.05	0.78	4.82	0.50	0.04		0.00	0.00	0.01
Share (total)					0.40		0.00	0.00	0.03

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\mitigation efforts\"selection of activities and mitigation measures to be displayed in the table"

Figure 34. Isolated details for the mitigation technology 'breeding for increased feed efficiency'

Mitigation efforts: Details [0]

Region: European Union | Product: Breeding for ruminant feed efficiency | Year: 2030

	Implementation share of mitigation option [Share]	Upper bound for implementation share of mitigation option [Share]	Accounting cost for mitigation efforts [Euro /ha or head]	(Secondary) revenue from mitigation efforts [Euro /ha or head]	Pmp cost or revenue (negative) of mitigation [Euro /ha or head]	Mitigation subsidies [Euro /ha or head]
All cattle activities	0.17	0.49	1.18		20.63	1.41
Dairy Cows high yield						
Dairy Cows low yield						
Other Cows	0.27	1.00	1.37		28.74	1.64
Heifers breeding						
Heifers fattening high weight	0.25	1.00	1.67		30.16	2.01
Heifers fattening low weight	0.34	1.00	1.06		18.00	1.27
Male adult cattle high weight	0.26	1.00	1.52		28.19	1.83
Male adult cattle low weight	0.33	1.00	1.01		17.23	1.21
Raising male calves	0.46	1.00	1.32		21.46	1.59
Raising female Calves	0.43	1.00	1.13		19.23	1.36
Fattening male calves	0.69	1.00	1.25		16.35	1.49
Fattening female calves	0.63	1.00	1.63		21.15	1.96
Other animals	0.05	0.05	1.06		2.58	1.27
Pig fattening						
Pig Breeding						
Milk Ewes and Goat						
Sheep and Goat fattening	0.97	1.00	1.07		2.61	1.29
Laying hens						
Poultry fattening						
All agricultural activities	0.04	0.11	0.42		4.62	0.50

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\mitigation efforts: details\"creation of the desired table through right mouse click on control button "pivot" in the upper right corner"

Figure 35. Consequences of the mitigation measure 'breeding for increased feed efficiency' on the emissions of different GHG types

Environmental indicators [0]

Region: European Union | Year: 2030 | Scen: subscal_endotech_feff | Percentage diff. to Scen refpol_endotech_noc_sup

	Total [in 1000t]	Amount per ha [in 1000t/ha]	Impact in GWP [in 1000t CO2 eq]
Ammonium output	2525.88 -0.27%		
CH4 Total emissions	8498.18 -0.95%	47.30 -0.96%	212454.44 -0.95%
Emissions of CH4ENT	7150.30 -1.05%	39.80 -1.06%	178757.58 -1.05%
Emissions of CH4MAN	1278.37 -0.45%	7.12 -0.46%	31959.37 -0.45%
Emissions of CH4RIC	69.50 0.00%	0.39 -0.00%	1737.49 0.00%
N2O Total emissions	706.50 -0.37%	3.93 -0.37%	210537.38 -0.37%
Global warming potential from agriculture			422991.81 -0.66%

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\environmental indicators\"selection of activities and mitigation measures to be displayed in the table"

Figure 36. Methane emissions per activity in the scenario 'breeding for feed efficiency'

Methane emissions per activity, multiplied with activity levels [0]

Region: European Union | Year: 2030 | Scen: subscal_endotech_feff | View type: Table

	Methane output [kg/ha or hd]	Methane emissions from enteric fermentation (IPCC) [kg/ha or hd]	Methane emissions from manure management (IPCC) [kg/ha or hd]
All cattle activities	6822.53	6256.60	565.93
Dairy Cows high yield	1930.45	1714.30	216.14
Dairy Cows low yield	1555.36	1383.80	171.56
Other Cows	1066.81	1021.45	45.36
Heifers breeding	748.45	707.40	41.05
Heifers fattening high weight	158.69	148.83	9.86
Heifers fattening low weight	77.83	73.70	4.14
Male adult cattle high weight	369.36	345.26	24.10
Male adult cattle low weight	168.88	158.82	10.06
Raising male calves	277.27	261.45	15.82
Raising female Calves	347.53	326.43	21.10
Fattening male calves	79.71	75.44	4.27
Fattening female calves	42.17	39.72	2.46
Other animals	1606.15	893.70	712.45
Pig fattening	704.25	141.59	562.65
Pig Breeding	129.64	18.67	110.97
Milk Ewes and Goat	554.22	539.98	14.24
Sheep and Goat fattening	198.93	193.46	5.47
Laying hens	7.01		7.01
Poultry fattening	12.10		12.10
All agricultural activities	8498.18	7150.30	1278.37

How to get to this table in the GUI: exploit results\"selection of settings (i.e. countries to display, regional level, simulation year, etc.) and the corresponding scenario"\environment\manure, N2O and methane\methane emissions per activity, multiplied with activity levels

References

Britz, W. and P. Witzke (2014): CAPRI model documentation 2014, http://www.capri-model.org/docs/capri_documentation.pdf.

Mottet, A., Gerber, P., Weiss, F., Eory, V., Witzke, P., Huck, I., Carmona, G., Kuikman, P., Silvestri, S., Havlik, P. (2015): Report on the quantitative analysis of policy issues, including methodology and results. Animal Change project, Deliverable 14.4. http://www.animalchange.eu/

GAINS database (2013): Greenhouse Gas and Air Pollution Interactions and Synergies. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. http://www.iiasa.ac.at/web/home/research/researchPrograms/GAINS.en.html.

GAINS database (2015): Greenhouse Gas and Air Pollution Interactions and Synergies. EU-28: GAINS model input data and results. Internal document produced for the JRC by the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Höglund-Isaksson, L. (2015): GAINS model review pf potentials and costs for reducing methane emissions from EU agriculture. Internal document produced for DG CLIMA by the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.