Will French beef and dairy farms reduce their GHG emissions by 2035?

Claire Mosnier, Anne Duclos, Jacques Agabriel, Armelle Gac

Will French beef and dairy farms reduce their GHG emissions by 2035?

MOSNIER Claire (1), DUCLOS Anne (1), AGABRIEL Jacques (1), GAC Armelle (2).

(1) INRA, UMR 1213 Herbivore, 63122 Saint-Genès Champanelle, cmosnier@clermont.inra.fr
(2) Institut de l'élevage – Monvoisin - 35652 Le Rheu cedex

Will French beef and dairy farms reduce their GHG emissions by 2035?

MOSNIER Claire (1), DUCLOS Anne (1), AGABRIEL Jacques (1), GAC Armelle (2).

(1) INRA, UMR 1213 Herbivore, 63122 Saint-Genès Champanelle, cmosnier@clermont.inra.fr
(2) Institut de l'élevage – Monvoisin - 35652 Le Rheu cedex

Abstract

The agricultural sector is called upon to reduce its greenhouse gases emissions. A scenario approach has been developed to explore the plausible futures of the French bovine sector and their impacts on climate change. These scenarios encompass a trend scenario (S1) and alternative contrasted scenarios: further intensification and export of bovine production (S2), development of grassland based organic farming (S3) and committed policy to reduce GHG emissions (S4). These scenarios have been evaluated both at national and farm levels. This paper focuses on the farm level approach. The bio-economic model Orfee has been created and used to assess the impacts of the main drivers of these scenarios on the evolution (production, economics, GHG) of typical French beef and dairy farms. These drivers encompass technological progresses (higher milk yield, younger first calving, legume fodders, higher efficiency of fertilizer), increase in labor efficiency, organic farming with low concentrates and tax on GHG emissions. For the trend scenario, this study shows that technological progresses foster milk production and raise profit and GHG emissions of dairy farms but GHG emissions per milk unit are improved. Under 2010 prices and without coupled public supports, beef production would decrease in suckler cow farms that are hardly profitable. GHG emission efficiency would be improved, thanks namely to younger age at first calving. Alternative scenarios underline that further production intensification doesn't necessary improve GHG emissions per output unit and that in some cases organic farming with low concentrate feed reduces emissions per unit of product and per farm but with lower production levels. A tax on GHG emission decreases emissions and livestock production, it would be particularly detrimental to suckler cow production.

Key words: Greenhouse gas emissions, cattle farms, bioeconomic model, prospective, intensification

1. Introduction

Paris Agreement (COP21, 2015) acknowledges the need to limit the temperature increase to 2 degrees Celsius to avoid the worst climate impacts. 188 countries have committed to reducing their greenhouse gas (GHG) emissions and have set out a roadmap. The French low carbon national strategy targets a reduction of 12% of agricultural emission in 2028 relative to 2013 and of 50% between 1990 and 2050[1]. The agricultural sector contributes to 19% to national emissions (Citepa 2015). With a population of 19 million of bovine, beef and dairy cattle productions are the main contributor to agricultural sector GHG emissions (60%). Evolution of the bovine sector in the next 20 years would be crucial to meet the GHG emissions target. This evolution would depend on numerous factors including technology, production organizations and markets, human population growth and consumer demand, climate change and policy.

The Gesebov project has investigated the joint evolution of the dairy and beef cattle sectors in horizon 2035 and its associated level of GHG emissions at farm and national levels. The scenario approach is a widely used method to explore a highly uncertain future for agriculture (Abildtrup *et al.* 2006; Audsley *et al.* 2006; Mandryk *et al.* 2012) by describing coherent and plausible future states of the world. Since emissions of GHG by the bovine sector are first explained by the bovine inventory (Casey & Holden 2006b) and second by the way meat and milk are produced (Monteny *et al.* 2006; Johnson *et al.* 2007), Gesebov scenarios have been specifically elaborated to be contrasted in terms of volume and technology of bovine production. The impacts of those scenarios on climate change were assessed at national level and at farm level. National level analysis provide estimates of beef, meat and GHG produced in France. Farm level analysis provide information regarding the potential evolution of heterogeneous farming systems (technical, economic and environmental). This paper focuses on the farm scale. Farm scale models enables to study relationships between production and GHG emissions per unit of product (Schils *et al.* 2007; Crosson *et al.* 2011). Bio-economic farm models can simulate impacts of new technologies or changes in the socio-economic environment on farming systems (Lien & Hardaker 2001; Louhichi *et al.* 2004; Janssen & van Ittersum 2007; Lengers *et al.* 2013; Kanellopoulos *et al.* 2014).

The objectives of this paper are to simulate which technologies would be adopted by some typical suckler cow and dairy farms according to scenarios, and to assess whether evolution of GHG emissions are compatible with climate change mitigation objectives. Technologies encompass increased milk potential, younger age at first calving for beef and dairy cows, fodder legumes, cropping activities with practices ranging from organic to intensive and higher fertilization efficiency. Simulations are run for typical French suckler cow and dairy farms with the bio-economic model Orfee developed for that purpose.

[1] Décret n° 2015-1491, http://www.gouvernement.fr/conseil-des-ministres/2015-11-18/l-adoption-de-la-strategie-nationale-bas-carbone-pour-le-cli

2. Material and methods

2.1. Model description

The bio-economic model Orfee aims at simulating a large range of farms producing beef, milk, annual crops and/or grasslands. It provides indicators of production, economic performance and GHG emissions. Farm functioning is modeled for an average year, at a steady state, with a monthly level of disaggregation. This model is run in Gams (GAMS development Corporation, 1217 Potomac Street W; Washington, DC 20007, USA) and resolved by the linear solver CPLEX. A short description is provided in the following subsections, but a detailed documentation is available in the supplementary material.

Focus has been made on technology that could potentially affect GHG emissions such as productivity per animal (age at first calving, type of animal product, milk yield, breed, calving period..), protein self-sufficiency with the possibility to introduce alfalfa or a mixture of cereal and protein crops in the foraging systems and in animal diets, animal diet composition and fertilizer consumption (various production intensity from organic to intensive farming). Decisions that could be optimised to maximize net profit concern crop and grassland production, animal production and animal diets, buildings and materials.

2.1.1. Cattle module

Animal categories are defined by three sets: breed, type of animal and calving period (or period of birth). The most widespread cattle productions in the studied regions are included: calves, weanlings, heifers and young bulls, culled cows, steers and milk production. Heifer for reproduction could calve at 24-month-old, 30-month-old or 36-month-old. Breed modifies animal characteristics: live weight growth and carcass weight, intake capacity, reproduction performance, milk production etc... Breed proposed in the model encompass the one predominantly present in France Charolais, Limousin and Salers for beef breeds, Holstein, Montbéliarde and Normande for dairy ones. Different calving periods are possible (autumn, winter spring, summer) in order to control calves mortality or to better match feed or labour requirements with farm resources.

Feed requirements are calculated on a monthly basis for each animal category to cover animal needs for maintenance and gestation, milk production and growth. Intake capacity, net energy and protein requirements are calculated thanks to the Inra methodology (INRA 2007). It provides flexibility to adapt diet composition to production contexts. Optimisation constraints impose that 1) energy and protein content of each animal diet (averaged monthly) meet animal needs, 2) fill value of animal diets equals their intake capacity (except at pasture where fill value could be 30% below intake capacity), 3) the concentrate feed doesn't exceed a maximum value[2] and 4) feed could be available. Demographic constraints between animal categories enable to ensure that herd composition is balanced and respect the reproduction and ageing process.

Four types of effluents are defined according to their straw and water content: compact manure, soft manure, diluted effluent and liquid manure. The quantity of manure produced depend on the type of building, of animals and of the length of the indoor period. Operations (feed distribution, milking, reproduction monitoring etc.) and housing needs are specified too and impact directly on labour needs.

2.1.2. Crop module

Crop rotation is considered to be a « cornerstone of 'integrated farming', (Leteinturier et al., 2006). In this model, production intensity, inputs and outputs are explicitly linked with crop rotations. Crop activities are the combination of three sets. The first one corresponds to the combination between previous crop-current crop family. Objective of these crop families is to group crops that could have the same agronomic behaviour regarding crop successions. The second one specifies the end use or precise crop specie. To cover main current crop productions as well as crops that could reduce fertilisation and plant protection and improve animal feed self-sufficiency, 11 crops (wheat, barley, triticale, corn, rapeseed, sunflower, peas, mix of protein and cereals, alfalfa, temporary and permanent grass) are introduced with various end uses (silage, grain, number of grass cuts..). Eventually, the third set indicates the crop intensity. The conventional crop intensity corresponds to average observation in the studied areas. Definitions of intensive and integrated farming are based on the terminology used in the "Ecophyto" project[3]. The intensive level targets the yield potential and use phytosanitary treatments without limitation (roughly +30% of treatments, +4% yield compared to conventional level). Integrated level aims at reducing the use of inputs (-30% of phytosanitary products in average) while accepting lower yield (-6% in average). Organic is defined upon the standard of this label, without phytosanitary treatment and mineral fertilisation. Nitrogen requirements are estimated thanks to the nitrogen (N) balance approach, they depend on previous crops, crop intensity and soil quality. Crop operations (tillage, seeding, spreading, cutting, harvesting, etc.) are defined on a monthly basis, based namely on Arvalis data (Boigneville experimental farm).

Optimization constraints concern non tillable lands that should be allocated to permanent grasslands, maximum share of a crop activity in tillable area according to crop intensity, equilibrium between previous crop-current crop activities, satisfaction of fertilizer and crop operation requirements.

---

[2] 30% except for dairy cow: 70% and during fattening periods: 50%

[3] http://institut.inra.fr/Missions/Eclairer-les-decisions/Etudes/Toutes-les-actualites/Ecophyto-R-D, p8

2.1.3. Stable and machinery

Crop operations could be implemented thanks to different types of machines. Labour, fuel consumption, gas emissions and machinery cost vary according to the type of machine[4]. The type of milking and feed distribution materials is parameterized by the operator. They affect labour required for the different herd operations, feeding system (no grazing with milking robot), machine costs and fuel consumption.

Optimisation constraints ensure that there is enough place in a suitable barn to house animals that should be kept indoors or milked, enough manure storage capacity and enough material to realize crop operation. Machine costs for crop operations are proportional to their use. Building costs are proportional to their area or capacity and to their characteristics (free stalls, cubicle and manure pit type).

2.1.1. Labor module

The quantity of labor required encompasses the time to monitor calvings and calves during their first days. It is proportional to the number of calvings. Time to milk dairy cow is proportional to the number of dairy cows producing milk a given month. Time to clean and renew litter is proportional to the number of animal present in a barn each month. Feeding time is calculated upon animal diets (proportional to the quantity of feed distributed). Additional time requiring handling animals (vaccinations and other seasonal operations) is fixed per livestock unit (LSU). Labor associated to crop activities is proportional to the time calculated to carry out the different operations (tillage, transport, conditioning, etc.). Data comes from descriptions of some farm types (Charroin *et al.* 2005), surveys on dairy and beef cattle farms (Cournut & Chauvat 2010; Fagon & Sabatté 2010; Kentzel 2010) and from a survey of the regional extension service of Bourgogne [5]. Optimization constraints related to labor specify that labor needs per month and per year mustn't exceed the allowed workload per worker unit.

2.1.2. GHG emissions

Thanks to a Life Cycle Assessment (LCA) approach, climate change impact associated with all the stages of an agricultural product's life from cradle to farm exit gate are assessed. Three gases contributes to global warming: methane (CH_4), nitrous oxide (N_2O) and carbon dioxide **(**CO_2)

Methane emissions come from enteric fermentation and excreta of animals and are estimated with IPCC Tier2 or Tier 3 approach (Dong *et al.* 2006). Enteric methane emission factor (EF) is calculated according to Sauvant (Sauvant *et al.* 2011) using the equation 9[6] where EF is expressed in g CH_4/kg DOM. DOM is the amount of Digestible Organic Matter ingested by the animal, calculated by the

---

[4] http://www.loiret.chambagri.fr/fileadmin/documents/Machinisme/Bareme_VITI_ARBO_Edition_2013.pdf

[5] http://www.bourgogne.chambagri.fr/uploads/media/plaquette_Le_travail_en_%C3%A9levage_laitier_01.pdf

[6] Also reported in (Sauvant & Nozière 2016) eq 48

product of the amount of organic matter ingested (OM, kg) by OM digestibility (dOM) of the diet. This latter is equal to the average dMO of diet with three corrective parameters[7] to take into account digestive interactions (Sauvant & Nozière 2016): the quantity of dry matter intake per unit of live weight (DMI%LW), the amount of concentrate feed (CO) and the rumen protein balance (RPB). EF is a second degree polynomial function involving DMI%LW and CO in animal diet. Globally, this emission factor decreases when the quantity of dry matter intake per kg of live weight increases and when the amount of concentrate feeds exceeds 30%. To estimate methane from dejections, we use IPCC equation 10.23(Dong *et al.* 2006). Following Eugène *et al.* (2012), the daily volatile solid excreted is estimated by the non-digestible organic matter ingested by animals which is the difference between total organic matters ingested and the digestible organic matter ingested. Urine components of volatile solid were assumed negligible.

Nitrous emissions are divided into direct emissions from manure management and managed soils and indirect N_2O emissions that arise from volatilization of fertilizers, and nitrogen (N) lost via runoff and leaching from agricultural soils. N_2O emissions from manure management systems, calculated according to IPCC Tier2- Tier 3 (Dong *et al.* 2006), are proportional to the quantity of N excreted by animals. N excretion is calculated for each animal activity and month by the difference between N ingested *via* conserved feed or fresh grass and N fixed by meat and milk (equation 10.33). N excretion is then allocated to the different manure management systems according to the time spent in a given barn or paddock. Direct emissions of N_2O from managed soils are computed according to IPCC Tier 1 (De Klein *et al.* 2006). They take into account manure spreading and inorganic N fertilization, annual amount of N in crop residues and from pasture renewal and the annual amount of urine and dung N deposited by grazing animals on pasture. Indirect N_2O emissions has been estimated based on the nitrogen balance calculated on a farm scale (Simon & Le Corre 1992).

Indirect CO_2 emissions of inputs purchased are estimated thanks to Dia'terre methodology (ADEME 2010). CO_2 may be emitted from or sequestered into agricultural soils. Assumptions made here rely on (Soussana *et al.* 2010). We suppose that permanent grasslands store 570 kg C/ha/yea, annual crops destock 160 kg C/an/year, temporary grasslands store 570 kg C/ha/an and then destock 950 kg/year the two years following grassland destruction. Note that CO_2 emissions from liming and urea fertilization have not been accounted for since these operations have not been introduced in the set of crop operations.

The three gases are aggregated by their potential of global warming into a single indicator expressed in CO_2 equivalent (CO_2e). Values are those proposed by IPCC ((Forster *et al.* 2007), p212, 100-year time horizon): CO_2 =1; CH_4 = 25; N_2O = 298. Emissions are computed at farm level and by unit of animal

[7] equation 24

product. To estimate net impact of livestock production on climate change the quantity of carbon stored (net CO_2e) in soils have been deducted from total emissions.

Emissions are computed at farm level and by unit of animal product i.e. kg of milk and kg of live weight (kglw), without consideration of their quality (fat nor protein content). A biophysical allocation, as applied in the French AGRIBALYSE® program (Koch & Salou 2014) is used here to share the environmental burden of the systems between milk and meat. A ratio of energy requirement for lactation and maintenance on total energy requirements of dairy cows is used to allocate impacts to milk production; the rest of the impact is allocated to meat production from dairy cows.

2.1.3. Objective function

Net profit is defined as total revenues including sales from animal (milk, carcass, lean animals) and crops, and compensatory payments (decoupled payments, suckler cow payments, grass payments, least favoured area payment etc.) minus total costs encompassing herd and crop variable costs, machinery (fuel, depreciation and maintenance cost or enterprise cost) and buildings (depreciation and maintenance) costs.

2.1. Case studies

Four farm types have been selected within the Inosys-Réseaux d'élevage referential[8] (Charroin *et al.* 2005) to cross cattle production orientation with land characteristics: a dairy farm with permanent grassland only (DC_Grass) in Normandy (oceanic climate north-west of France), a dairy farm with temporary grasslands and annual crops (DC_Crops) in Pays de la Loire (west of France), a suckler cow farm with permanent grasslands only (SC_grass) in the mountains of Cantal (south Massif Central centre of France), and a suckler cow farm fattening young bulls with grasslands and annual crops (SC_Crops) in the North of Massif Central (table 1). Further details are provided in Appendix 1.

Table 1: Main characteristics of the farm types selected

	SC_GRASS	*SC_CROPS*	*DC_GRASS*	*DC_CROPS*
WORKER UNIT	*1.5*	*2*	1.5	1.7
HERD SIZE (LSU)	*86*	*251*	63	73
MEAT PRODUCTION (LIVE KG /LSU)	*309*	*384*	na	na
BREED AND ANIMAL PRODUCTS	*Salers and crossbred Cow, weanlings*	Charolais cows, heifers, young bulls	Normande Cow, heifers, newborn calves	Holstein Friesian, Cow, newborn calves
MILK QUOTA (TONS)			200	390
MILK YIELD (1000 L/COW)			5,7	7,8

[8] Inosys-Réseaux d'élevage builds description of typical farm types per region thanks to a large network of commercial farms and expert knowledge

STOCKING RATE (LSU/FORAGE AREA)	1,0	1,4	1,1	1,5
CEREALS (HA)	0	67	0	11
OILSEEDS (HA)	0	35	0	0
SILAGE CORN (HA)	0	10	0	13
TEMP. GRASSLANDS(HA)	87	42	55	0
PERM. GRASSLANDS (HA)	0	126	0	37
SUBSIDIES (K€)	44	*103*	15	21
NET INCOME BEFORE SALARIES (K€)	21	*104*	17	46

Note: LSU = livestock unit (equivalent to 1 dairy cow over a whole year)

2.2. Scenarios

Two kinds of scenarios have been developed. The trend scenario **(S1)** is considered as the most probable from the 2014 perspective. It has been elaborated considering past trends and the most likely evolution of technology and markets (Idele 2014). Alternatives scenarios have been constructed by expert groups gathering people working in the beef and dairy sectors and researchers, to explore other plausible futures (table2). For the trend scenario **S1,** it is assumed that at national level dairy production would increase taking advantage of new opportunities to export while suckler beef production (-11% of suckler cows) would shrink because of a reduction in outlets for exports and an increase of beef produced by the dairy herd. Scenario **S2** assumes an expansion of beef and above all dairy production to meet the raising global world demand. Farm enlargement would be accompanied by a high increase in labor efficiency and a high level of mechanization (without additional costs thanks to the high level of diffusion of technological progress). The scenario **S3** considers the opposite situation with the development of a local environmentally friendly production based on grasslands with double purpose breeds (Normande, Montbeliarde). It is associated to a decrease in the quantity of beef and milk produced and consumed. Eventually, the scenario **S4**, depicts a situation where the reduction of GHG emission is a priority and is enforced by a proactive policy and by a growing vegetarian population. These scenarios are compared to the baseline scenario ***B0*** which reproduces the farming systems for the average economic situation of 2008-2013.

Table 2: Main characteristics of scenarios at national level

	S1 «Trend »	**S2 «Production +»**	**S3 « Grass+ »**	**S4 « GHG »**
Context	Low economic growth and demand in France.	Increase of production to answer a high global demand, export ++	Fold on an internal demand which goes upmarket	Large drop in consumption, high level of constraints for GHG emissions
National production	milk : +36% ; ↑export beef : + 6%; ↓export	milk : + 60% beef : +16%	milk : +7% beef : -14%	milk : -21% beef : -32%
Production systems	Concentration + Enlargement + mechanisation +	Concentration ++ Enlargement ++ mechanisation ++	Concentration -- Enlargement -- mechanisation --	Concentration - Enlargement = mechanisation +

	intensification per animal +	intensification per animal ++	intensification per animal --	intensification per animal : both -/+

The main technological progresses and socio-economic drivers of the scenarios were selected to simulate their effects at farm level (table 3). In order to facilitate the interpretation of results, a voluntary limited number of factors have been modified between scenarios.

A set of new technologies is proposed for all 2035 scenarios (S1-S4). These technologies can be adopted or not according to farm type and scenarios (decision is endogenous). Holstein Friesian dairy cows with higher milk potential (10000L/cow max.) are proposed in addition to the actual Holstein Friesian (8000 L/ cow) and Normande breed (6000 L/cow). Milk yield is indeed expected to rise but genetic potential improvement would slow down in the future (+25%) compared to past trends (+50% in average between 1990 and 2010). 10 000 L-milk-yield cows are supposed to be fed indoors only because of the high energy content of their diet. They are also slightly heavier (+3.5%) in order to have an intake capacity compatible with their requirements. Although carcasses have enlarged over the past (+13% between 1990 and 2013 (Veysset *et al.* 2015)), according to experts heavy carcasses don't meet anymore the market demand. Consequently, we assume constant carcass weight for beef breeds. Given practices currently observed in other countries, first calving would be possible three months younger for beef and dairy breeds in 2035. The fertilization efficiency has progressed a lot during the past decades in the studied systems (at least -20% of mineral nitrogen fertilization between 1990 and 2010) and would continue to progress but at a smaller rate (10% less of nitrogen is required for the same average yield in 2035). Eventually, legume fodder and mixture of cereal and protein crops are supposed to be accessible everywhere land is tillable. Regarding prices, milk, beef and cereal prices are set at baseline for scenarios S1 to S4 (average over the period 2008-2013). A sensitivity analysis of the results to beef and dairy prices are nonetheless provided in *appendix 2* given uncertainties related to milk and beef prices. Similar to Kanellopoulos et al (2014), fuel and fertilizers prices are assumed to increase by 40%. Regarding policy, simulations are made without subsidies. We know that the current CAP policy will be reformed but we don't make hypothesis on the issues of future negotiations.

Differences between scenarios arise from the doubling of labor productivity in **S2 (**more than +100% were observed between 1990 and 2010 (Veysset *et al.* 2015)). This implies both a reduction of production cost and an increase of the production capacity since labor is a limiting resource on the farm. In **S3,** we test the obligation to produce organic products with not more than 10% of concentrate feed in the total dry matter intakes. Similar to the current French situation, organic prices are 20% higher of milk and 15% higher for animals ready to be slaughtered. Eventually, a tax on carbon net emissions, equal to 40€/t CO_2e, is enforced in **S4**. This value is in line with assumptions used in several studies (IPCC 2007; De Cara & Jayet 2011).

Farms could adapt to the different scenarios by modifying building and machinery capacities, crop activities, herd size, production per animal, animal feeding and variable inputs. Nonetheless, the type of animal product selected can be modified only at the margin. The farm that fattens animals (SC_crops) could produce steers instead of young bulls but couldn't produce weanlings; similarly the farms producing only weanlings (SC_grass) can sell weanlings at different ages and steers but not finished young bulls. Dairy farms could opt for a different dairy breeds (Holstein Friesian or the dual-purpose breed Normande) and produce steers. Farm structure (worker unit and arable area) is considered a constant.

Table 3: Summary of assumptions in the simulated scenarios

B0	Baseline price (average 2008-2013)
S1-S4	- Prices =B0 (standard milk = 335€/ton, charolais culled cow = 3.5 €/kg carc, wheat =187€/t), fuel and fertilizers: B0 x1.4 - First calving three month younger possible - Same breeds as S0 + Holstein Friesian 2035 : milk yield +30%, liveweight+3.5%, fed indoors - Free calving periods - Mixture of cereal_protein crops, alfalfa - Increase of fertilisation efficiency (+10%)
S2	Labor productivity x2
S3	Organic farming with 10% max. of concentrate feed (organic milk price x 1.2, beef carcass price x1.15, lean animals 1.1 , crop price ≈ x 2)
S4	Tax on net carbon emission (40€/ t)

3. Results

3.1. Global GHG emission and production at farm level

Evolution of total gross emissions of GHG at farm level follows roughly variations of cattle production (figure 1 and 2) even if the technology of production impact also on total GHG emissions: production and GHG are globally higher in 2035 scenarios than in the Baseline for dairy farms and lower for suckler cow farms. Nonetheless variations between scenarios are important.

In the trend scenario **S1,** milk production is multiplied by 1.5 in the dairy cow farm with annual crops (DC_Crops) (figure 1). It increases even more in DC_Grass (x2.5) which specializes in milk production and switches dual-purpose Normande cows for more productive Holstein Friesian ones. Because of the highest increase in milk yield, meat production augments in smaller proportion in DC_Grass (+12%) than in DC_Crops (+23%). Regarding suckler cow farms, meat production decreases (-8% in SC_Grass and -35% in SC_Crops). Temporary grasslands are replaced by cash crops in SC_Crops (figure 3). In the case of DC_Crops, oilseeds, alfalfa and the mixture of cereals and protein crops expand at the expense of temporary grasslands. Total **gross GHG emissions** are multiplied by 1.6, 1.3, 1.1 and 1 in DC_Grass, DC_Crops, SC_Grass and SC_Crops, respectively. Change in **net emissions** are particularly important in DC_Grass since sequestration compensates 41% of gross emissions in the baseline but only 26% in S1 (stocking rate increases).

In scenario **S2**, the gain in labor efficiency reduces production costs and allows more cows or cash crops per worker unit. Cattle production increases slightly in suckler cow farms (+7% for DC_Grass; +4% for SC_Crops relative to S1) and strongly in dairy farms (+33% for DC_grass; +57% for DC_Crops). All crops grown on DC_crops are used to feed animals while SC_Crops maintains the maximum area with cash crops. Total **gross GHG emissions** are multiplied respectively by 1.3, 1.6, 1 and 1.1 relative to S1 in DC_Grass, DC_Crops, SC_Grass and SC_Crops.

The **scenario 3** imposes organic farming with less than 10% of concentrate feed. Grasslands and alfalfa expand on tillable lands. Beef produced in suckler cow farms and milk are close to their baseline level thanks to organic prices which are more attractive than conventional ones. Total **gross GHG emissions** are multiplied in average by 0.8 relative to B0. **Net emissions are reduced** by up to 35% thanks to a reduction of animal stocking rate.

In scenario **S4,** taxes on GHG induce a reduction of beef production in suckler cow farms by half. Dairy farms produce quantities of beef and milk comparable to the trend scenario (S1), alfalfa partly replaces annual fodder crops because it is assumed to store more carbon. Total **gross GHG emissions** are multiplied respectively by 1.4, 1.2 and 0.7 and 0.1 in DC_Grass, DC_Crops, SC_Grass and SC_Crops. **Net emissions are negative** in the case of SC_Grass (carbone storage in grasslands exceeds GHG emissions).

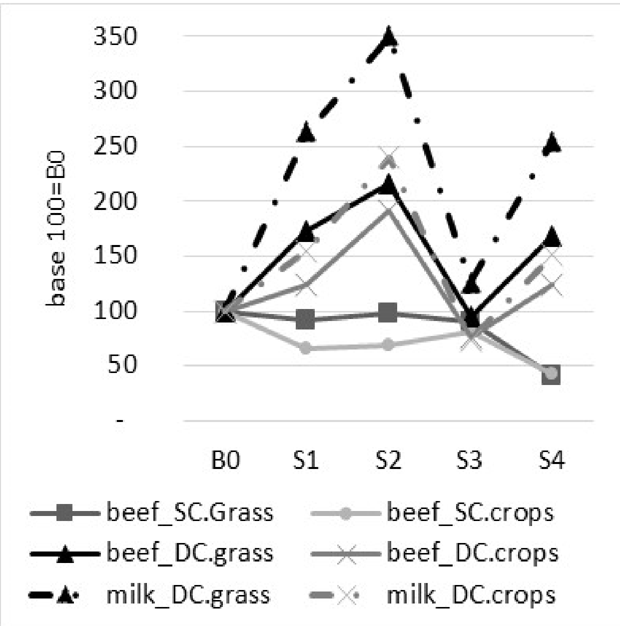

Figure 1 : Evolution of beef and milk production per farm

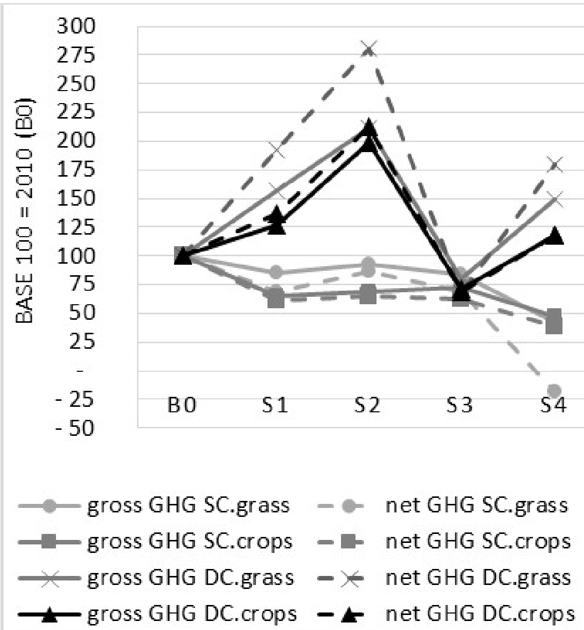

Figure 2 : Evolution of gross and net GHG emissions per farm

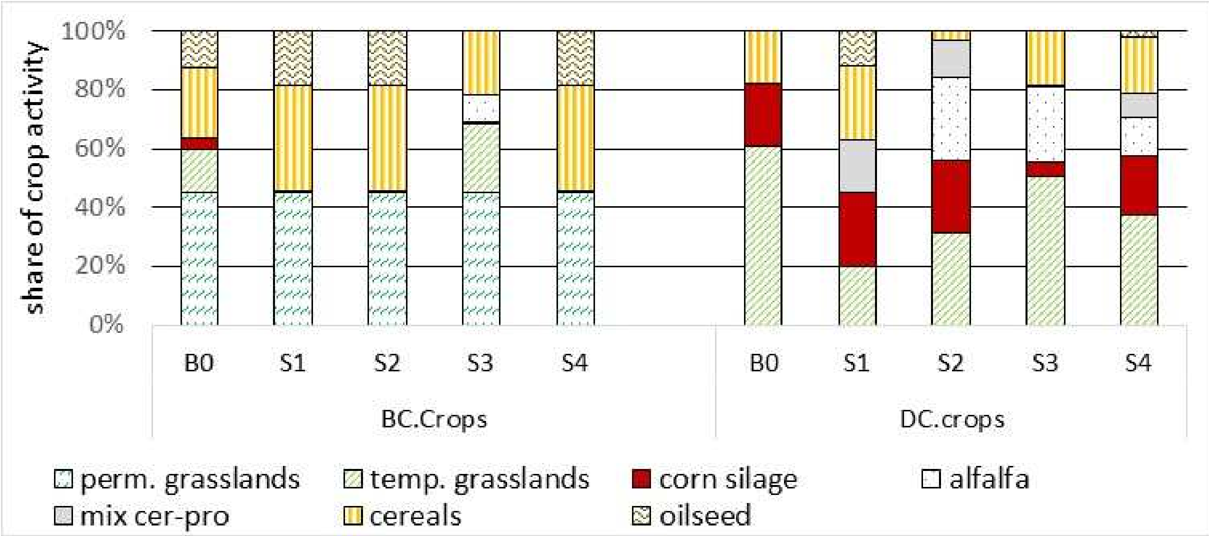

Figure 3: Share of crop activities (in % of the total area)

3.2. GHG emission efficiency and production technology

For suckler cow farms, gross GHG emissions per kg of live meat decreases between 4% and 10% in **S1** relative to B0. This benefit could be first attributed to younger first calving (≈-0.5 kg CO_2e /kglw[9]). Early calving raises meat production per LSU (between +3% and +5% relative to B0) with counterpart a slight increase in organic matter ingested to meet higher feed requirements of female heifers. A higher share of liquid manure in total manure production in SC_Crops (25% instead of 0% in B0) decreases N_2O and CH_4 emissions linked to manure management (cows are housed in cubicles with a liquid manure system). Spring calving instead of winter calving for SC_Crops (winter calving is retained in SC_Grass) and a better optimization of the system explain also these gains. GHG emissions in **S2** are rather similar to S1 since the production system is little impacted by the increase in labor efficiency. In **S3,** animal diets are significantly modified (figure 4). The introduction of grass silage reduces slightly CH_4 emissions for SC_Grass; the partial substitution of concentrate feed by green fodder and alfalfa increases CH_4 emissions for SC_Crops. Nonetheless, the reduction of the consumption of concentrate feeds and purchased fertilizer enable to reduce GHG emissions per kg of meat up to 5% relative to S1 and up to 14% relative to B0. **In S4,** beef production per hectare becomes very low in SC_Grass (0.5 LSU/ha), probably too low to prevent the emergence of shrubs. Gross emissions per kg of meat deteriorates because of weanlings sold younger. Net emissions become negative because carbon storage more than offsets GHG emissions.

[9] Additional simulations have been run to isolate effects of each 'technological progress'

For dairy farms, emissions per kg of milk decrease significantly **in S1** for DC_Grass (-16% in S1 compared to B0) and to a lesser extent for DC_Crops (-10% in S1 compared to B0). These gains are first obtained through an increase in milk yield. DC_Grass switches Normande for Holstein Friesian cows (average milk yield=8970 L/ cow, +61% relative to B0) and DC_Crops benefits from the increase in milk potential of Holstein Friesian (average milk yield= 9735 L/cow, +24%). It reduces enteric fermentation per milk unit (enteric CH_4: -30% for DC_Grass, -15% for DC_Crops) and N excretion per milk unit. The calving period chosen is spring. Younger first calving which is always chosen whatever the farm and scenario and the heaviest carcass of Holstein Friesian in the case of dairy farms (+3.5%) raises meat production and reduces GHG emissions per kglw (table 4). Because of the intensification of animal production per hectare in DC_Crops (from 1.4 to 2.2 LSU/ha), the share of grass based fodder shrinks while concentrate feed (30% of total DM intake) and crop fodders (corn, mix cereal-protein and alfalfa) take more importance in animal diets (figure 4). In **S2**, the gain in animal productivity is little and production intensifies per hectare. The consumption of feed concentrate is more important for all animal categories. GHG emissions allocated to beef increase significantly. In **S3**, milk yield strongly decreases (average milk yield: 6.5 tons of milk per cow in DC_Grass; 6 tons/cow in DC_Crops) because of the organic constraint and above all the limitation of feed concentrate consumption (< 10% of total DM intake). Stocking rates decrease and diets are based principally on grassland products and alfalfa. The increase in methane emission per liter of milk is partly offset by a reduction of CO_2 emissions for DC_Crops and more than offset for DC_Grass. Net emissions are reduced per liter of milk and meat. In **S4,** production systems are rather comparable to the trend scenario except that, in DC_Crops purchased concentrates decrease and alfalfa increases at the expense of corn silage. Emissions are lower than in B0.

Table 4: GHG emissions of suckler cow farms in kg CO_2e/kg of liveweight

		B0	S1	S2	S3	S4
	CO_2	1.29	1.05	1.14	0.71	1.10
	CH_4	9.86	9.71	9.63	9.58	9.81
	N_2O	3.63	3.43	3.46	3.13	4.28
SC_Grass	**Gross CO_2e**	**14.8**	**14.2**	**14.2**	**13.4**	**15.2**
	***Net* CO_2e**	***7.28***	***5.69***	***6.48***	***5.34***	***-3.23***
	CO_2	1.70	1.34	1.42	0.84	1.12
	CH_4	8.83	8.37	8.37	8.60	8.55
	N_2O	4.51	3.67	3.79	3.39	3.57
	Gross CO_2e	**15.0**	**13.4**	**13.6**	**12.9**	**13.2**
SC_Crops	***Net* CO_2e**	***12.2***	***10.1***	***10.4***	***9.1***	***8.8***

Table 5: GHG emissions in dairy farms (in kg CO_2e/kg of liveweight or per kg of milk)

	kg CO_2e/kg liveweight					kg CO_2e /kg Milk				
	B0	S1	S2	S3	S4	B0	S1	S2	S3	S4

	CO_2	1.35	1.95	2.95	0.74	1.81	0.09	0.17	0.19	0.02	0.17
	CH_4	7.05	4.75	4.38	6.50	4.77	0.58	0.46	0.44	0.58	0.46
	N_2O	3.41	2.44	2.64	3.03	2.34	0.22	0.13	0.11	0.12	0.12
	Gross CO_2e	**11.8**	**9.13**	**9.97**	**10.5**	**8.88**	**0.89**	**0.75**	**0.73**	**0.72**	**0.75**
DC_grass	***Net CO_2e***	***7.31***	***6.91***	***8.17***	***5.51***	***6.61***	***0.55***	***0.57***	***0.60***	***0.38***	***0.56***
	CO_2	0.87	1.61	2.22	0.45	1.31	0.11	0.13	0.14	0.03	0.11
	CH_4	5.71	4.67	4.28	5.26	4.71	0.49	0.44	0.44	0.59	0.44
	N_2O	2.69	2.17	2.16	2.28	2.12	0.13	0.08	0.08	0.11	0.09
	Gross CO_2e	**9.26**	**8.46**	**8.67**	**8.04**	**8.15**	**0.73**	**0.66**	**0.65**	**0.73**	**0.65**
DC_crops	***Net CO_2e***	***8.52***	***8.34***	***8.50***	***7.20***	***7.48***	***0.68***	***0.65***	***0.64***	***0.65***	***0.60***

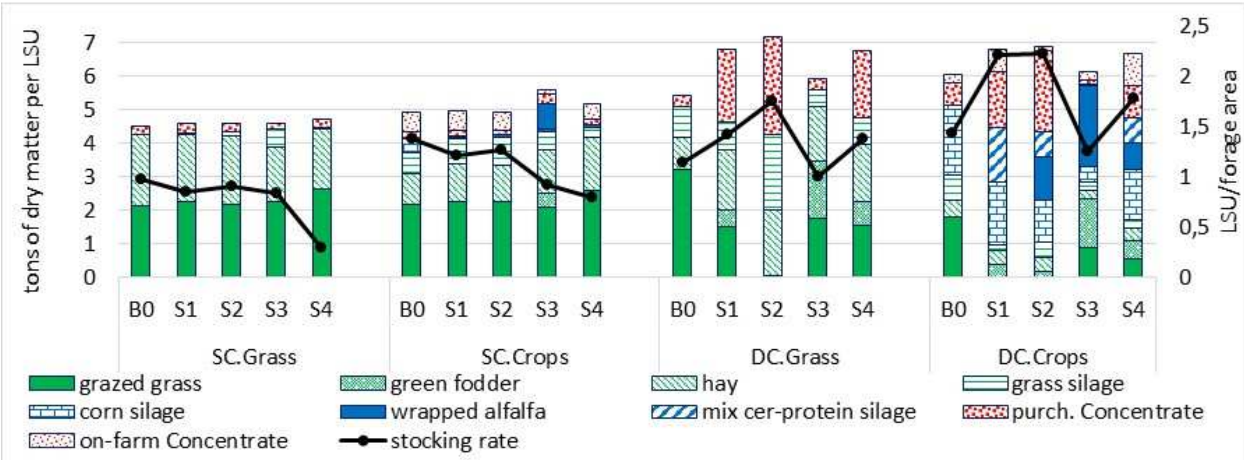

Figure 4: Quantity of feed in animal diets

3.3. Economic results

Economic results (figure 5) are analyzed without public support (except for the tax on net GHG) and after salaries (included family worker salaries). Dairy cow farms have negative revenue for the baseline, but the increase in milk yield and the introduction of legume productions enable to raise net profit to positive level in **S1** (+26 k€ for DC_Crops and +35k€ for DC_Grass). In spite of an increase in net income compared to **S0** (+6 k€), the suckler cow farms located in mountainous areas couldn't stay in business in any 2035 scenarios without public supports, higher beef prices, new technologies or other sources of income. SC_Crops net income raises by 14k€ in **S1** because of the higher share of cash crops. The scenario **S2** is the most favorable to producers' net income thanks to higher production levels and lower labor costs. Net income are close between scenarios **S3** and **S4** but lower than the trend scenario (except for SC_Grass). S3 reduces farm sales while S4 taxes profit (15k€ per farm in average).

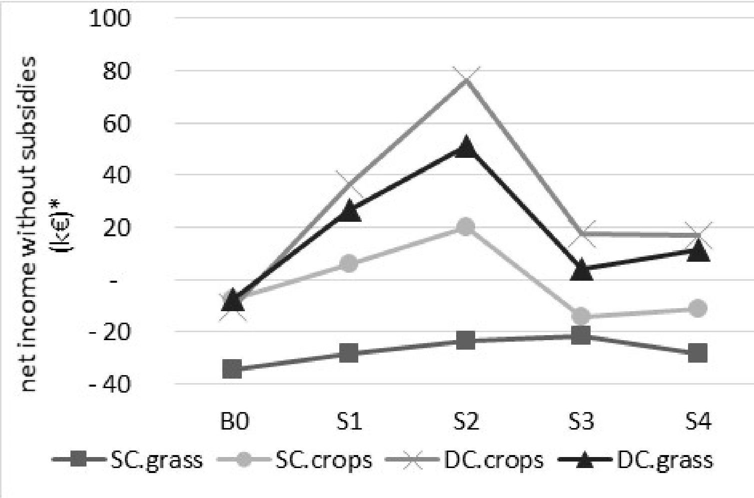

Figure 5: Net income without subsidies (except GHG tax) and after wages

4. Discussion

The main objectives of this study was to simulate how beef and milk production would be produced in the future and to assess how far the simulated scenarios were compatible with climate change mitigation objectives. Main results are that 1) in the future dairy farms are likely to increase their production per hectare while suckler cow farms would reduce it, 2) gross GHG emissions per unit of milk and meat would be reduced thanks namely to an increase in milk yield, younger age at first calving, spring calving and legumes fodders and 3) the most favorable scenarios for the reduction of GHG emissions at farm level involve the development of organic farming for suckler cow farms and grass based dairy farm and the introduction of a tax on GHG emissions for dairy farms with annual crops. In this section, we discuss the validity and limitations of 2035 projections and the GHG mitigation strategies.

4.1. Validity of the farm model simulations

The reliability of this bio-economic model could be assessed by its ability to reproduce production processes, estimate GHG emissions and calculate economic results in an appropriate level of details and to predict farmers' decisions in various context.

- Simulation of the production processes and farmers' decisions

Some calibrating method, such as Positive Mathematical Programming are often used to reproduce exactly the observed production decisions in adjusting automatically the production costs of the different farm activities (Heckelei & Britz 2005; Kanellopoulos *et al.* 2010). Nonetheless this method gets very complicated when activities are highly embedded, especially with animal production, and is not relevant for long term simulation in which technology could change drastically (Kanellopoulos *et al.* 2014). We opted instead for a calibration/ validation in two steps: 1) animal diets and crop operations were optimized for fixed levels of animal products and crop activities; 2) Crop allocation and herd size were also optimized for the average economic situation of 2008-2013, considering that building investments have been previously decided (short term optimization) and that milk quotas are still enforced. Technical and economic model outputs were compared to farm type referential from Inosys Réseaux-d'élevage (Charroin *et al.* 2005). When crop and animal activities were fixed (Appendix 1), we observe a good match for feed, fuel and fertilizer consumption and close economic results.

When these activities are also optimized[10], results show that 1) suckler cow production in mountainous area slightly decreases, 2) suckler cow production sharply decreases in SC_Crops where cash crops can be expanded. Nonetheless, the feeding systems are comparable, 3) the dairy cow production system based on grasslands (DC_Grass) maintains its level of milk production but reduces the number of heifers sold. Grassland production becomes more extensive while concentrate feed increases slightly, 4) milk production is maintained in DC_Crops but with a higher stocking rate so that cash crop production could increase. The model doesn't reproduce exactly the decisions observed for the period 2008-2013. Nonetheless, these decisions appear sensible since this period was more favorable to cash crop production than beef production. To reproduce more accurately current famers' decisions, it would be necessary to take into account the dynamic of past investments (Lengers *et al.* 2013) and farmers' expectation regarding the future (Nerlove & Bessler 2001). Nonetheless, we assume that the current investment situation of these farms would have little impact on their 2035 farming systems.

Results of the 2035 simulations show that younger age at first calving and in some cases legume based fodders become very attractive. The question is why these technologies would be more attractive in the future than now since these options already exist but are underdeveloped? Regarding age at first calving, the main bottleneck seems to be labor organization. Farmers prefer to delay the age at first calving in order to group primiparous cows calving with the highest chance of success. We can imagine that in the future, genetic selection of earlier sexual maturity (above all for beef breeds) and electronic developments or subcontracting of heifer breeding would help to monitor more carefully herd heterogeneity. Regarding alfalfa and the mixture of cereals and proteins, these crops are attracting increasing attention (7th Research Framework Programme of the European Union, ANR funded project Legitimes, etc.) and we could expect that when more information is available and analysis of feed quality more systematic, these crops will expand.

- Validity of GHG emissions indicators

There is a wide range of values in the literature regarding GHG emitted by bovine systems (Crosson *et al.* 2011). These differences stem from the productions systems themselves but also from the methods

[10] Note that in this optimization, the number of animals is optimized but the type of animal produced (weanlings, finished animals, milk) can be modified only at the margin (weanlings sold of different ages for instance)

of calculation of GHG emissions (parameters or equations more or less detailed) and of emission allocation to the different farm products (Nguyen *et al.* 2013b). Regarding beef production from suckler cow farms, (Crosson *et al.* 2011) reported values around 30 kg CO_2e/kg of carcass beef (≈15 kg CO_2e/ kg of liveweight) which matches with the values estimated in this study. Regarding dairy production, (Crosson *et al.* 2011) reported values ranging between 0.5 and 1.5 kg CO_2. Values simulated for the baseline scenarios lie between 0.7 and 0.9. These values could appear rather low. This could be explained first by the allocation method which only attributes emissions from dairy cows (and not heifers) to milk production and excludes the fraction of emissions linked to pregancy and weight gain (AGRIBALYSE® program, Koch & Salou 2014). Second, the calculation of methane production (Sauvant *et al.* 2011) provides slighlty lower values than IPCC Tier2 for animals with a high level of ingestion per unit of liveweight and/or concentrate feed in the diet, this is typically the case of dairy cows with a high milk yield (appendix 2). Nontheless, conclusions of the studies would have been the same with the IPCC Tier2 methodology for enteric fermentation.

4.2. Are possible evolutions of cattle farms compatible with climate change mitigation objectives?

- Impacts of scenarios on production technology and on GHG emissions per unit of product

Higher milk yield and younger age at first calving were chosen in almost all scenarios and farm types (except for milk yield in scenario S3). It enabled to reduce significantly methane emissions. As enteric methane is a leading source of GHG emissions, a strategy often put forward is indeed to increase the ratio of livestock ‘production’ to ‘maintenance’ thanks to faster growth, higher milk yields or shorter dry periods lactating cows (Monteny *et al.* 2006). Feed intake increases usually with energy expenditures. Nonetheless, the rumen activity is modified by larger diets and by diets with higher share of concentrate feeds, leading to a reduction of CH_4 emissions per unit of product (Monteny *et al.* 2006). The indirect CO_2 emissions linked to the consumption of concentrate feeds partly offset the reduction of methane emissions. It explains why organic farming associated to a low level of feed concentrate (scenario 3) presents the lowest emission per output unit for suckler cow systems and for dairy production based on grasslands. We also show that legume fodders can limit the increase of indirect CO_2 emisions induced by an intensification of the forage area. Taking into account carbon sequestration in grasslands, scenarios 3 and 4 (tax on GHG emissions) brings the best results in terms of net GHG emission efficiency.

In the literature, interests of intensification of animal production to improve GHG emissions efficiency is controversial. Regarding beef production, Cardoso *et al* (2016) demonstrate for instance that intensification of pasture production from degraded pasture to fertilized grassland and supplementary feeding during the finishing period lead to significant improvement of GHG emission efficiency. At the opposite, suckler cow grass based systems with low supplementary feeding in France (Veysset *et al.*

2010), moderate intensification (Foley *et al.* 2011) or organic farming systems in Ireland (Casey & Holden 2006a) appear as a valuable alternative to reduce GHG emissions per unit of meat. In dairy production, Nguyen *et al.* (2013b) estimate that more intensive French dairy production systems emit less GHG per milk unit while New-Zealand studies point that, for a given level of milk production per animal, milk production intensification per hectare reduces GHG emission efficiency (Basset-Mens *et al.* 2009; Adler *et al.* 2015). Gains obtained thanks to the intensification of the production systems are not linear and beyond a certain level of intensification, an increase in fertiliser use and concentrate feed consumptions offset the reduction of methane emissions.

Some mitigations options have not been introduced in this study (simplified cropping practices, techniques of fertilizer applications, use of lipids or nitrates in animal diets, manure storage coverage, biogas production, etc.). Beside the fact that reduction of GHG emissions could have been greater than estimated here, it could also affect scenarios comparison. It could be indeed less costly for large intensive (scenario 2) farm to invest in some mitigation options (Lengers *et al.* 2014). Nonetheless, investments can also be shared by several smaller farms to reduce their cost per unit of farm output.

Technologies chosen for each simulation are sensitive to many parameters, namely outputs prices. It was difficult for experts to estimate prices for each 2035 scenarios. Consequently, they were set at their baseline values. Appendix 2 shows that a variation of +/-15% of beef or milk prices would affect the volume of production but not the main conclusions, except that cattle production would be eliminated in some farms if prices decrease by 15% and a 40€ tax on GHG emissions is introduced. Production and market risks are also assumed to increase in the future because of climate change and trade globalization (especially in scenario 2). This would reduce incentive to invest and to intensify production per hectare and animal, except if farms are well insured (Mosnier *et al.* 2009; Mosnier 2015). Introducing this dimension in this modeling framework may have resulted in smaller technological differences between scenarios.

- Impacts of scenarios on production level, total GHG emissions and economic results

We simulated that GHG emissions, milk and beef production from dairy farms are likely to increase in all scenarios, except S3, and that GHG emissions and beef production from suckler cow farms are likely to decrease, especially if a tax on GHG emissions is introduced. Sensitivity analysis also emphasizes that cattle productions from farms with tillable lands are more sensitive to prices since they have more room to intensify their cattle production if the prices are good or otherwise to switch to annual cash crop production. This findings are globally in line with assumptions made at France level. At France level, the trend scenario projects an increase of beef and above all milk productions from dairy farms, mainly in north-west France and a reduction of beef production from suckler cow systems that would be maintained primarily on permanent grasslands. Milk and beef are interlinked. Zehetmeier et al (2012) demonstrate that if we need more suckler cow to compensate the reduction of the number of dairy cows, this may downgrade the GHG performance of the global bovine sector. Nonetheless it was assumed that milk surplus would be exported, thus the global performance of the bovine sector is maintained. Nonetheless, according to export-import scenarios, more or less milk and beef would be produced elsewhere, modifying the carbon footprint at global level. This underlines the necessity to analyse the milk and beef carbon footprint worldwide (Garnett 2009; Nguyen *et al.* 2013a; Cohn *et al.* 2014). In addition, our scenarios assume changes in per capita food consumptions. Scenarios 3 and above all 4 hypothesise a reduction in beef and milk consumption. According to Esnouf *et al.* (2011), a reduction of the consumption of animal products may induce an increase of vegetable food that would *in fine* have negative impact on global GHG emissions. The assessment of scenarios should then be extended to other agricultural products (cereal, vegetables, etc.). Other dimensions should also be accounted for since these scenarios could have major impacts on water and air quality (manure surplus, dust), biodiversity (namely in grasslands), rural development (employment, equal development between territories) or resilience.

5. Conclusion

In order to explore possible future changes for the beef and milk French sectors and for their related impact on climate change, a scenario approach has been developed. The objectives of this paper were to simulate, thanks to the bioeconomic model Orfee, which technologies would be adopted by typical suckler cow and dairy farms and to assess whether evolution of GHG emissions per unit of product and per farm were compatible with climate change mitigation objectives.

Originalities of this farm level study lies first in its systemic approach emphasizing the relationships between crop and herd management, economic and environmental results. Second, the detailed calculation of GHG emissions, particularly for enteric fermentation which takes into account digestive interactions, enable to test effects of production intensification per animal and per hectare on GHG emission efficiency. Eventually the same modelling framework is used for contrasted beef and dairy cow farms which enable to compare effects of drivers in a large range of situation. Main results are that 1) in the future dairy farms are likely to increase their production per hectare while suckler cow farms would reduce it, 2) gross GHG emissions per unit of milk and meat would be reduced through an increase in milk yield, younger age at first calving, spring calving and legumes fodders and 3) the most favorable scenarios for the reduction of GHG net emissions involve the development of organic farming or the introduction of a tax on GHG emissions but they are also associated to lower beef and milk production per hectare.

Nonetheless, impacts of these scenarios have been analyzed only partially. First, only a limited number of mitigation options have been introduced in this study, focusing on production intensification or extensification. Second, other dimensions -including air and water quality, biodiversity, energy consumption, rural development and employment and resilience of the farming systems- should be taken into account at farm and territorial levels to assess which scenario may be suitable. Eventually, this study should be complemented by an analysis at global scale, including other agricultural sectors and taking into account the evolution of human diets.

Acknowledgments: The authors would like to thanks Ademe for co-financing this project, M Eugène for checking methane emissions, experts who took part to this projects, Inosys Réseaux d'Elevage and Inra-Umrh for their production of technical and economic references on livestock farms, P. Veysset and C. Lebecq for their proofreading.

Abildtrup, J., Audsley, E., Fekete-Farkas, M., Giupponi, C., Gylling, M., Rosato, P., Rounsevell, M., 2006. Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach. Environmental Science & Policy 9, 101-115

ADEME, 2010. Guide la méthode complet Dia'terre. Version 1. 0. . ADEME. Paris 523.

Adler, A.A., Doole, G.J., Romera, A.J., Beukes, P.C., 2015. Managing greenhouse gas emissions in two major dairy regions of New Zealand: A system-level evaluation. Agricultural Systems 135, 1-9

Audsley, E., Pearn, K.R., Simota, C., Cojocaru, G., Koutsidou, E., Rounsevell, M.D.A., Trnka, M., Alexandrov, V., 2006. What can scenario modelling tell us about future European scale agricultural land use, and what not? Environmental Science & Policy 9, 148-162

Basset-Mens, C., Ledgard, S., Boyes, M., 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecological economics 68, 1615-1625

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B.J.R., de Carvalho, I.d.N.O., de Barros Soares, L.H., Urquiaga, S., Boddey, R.M., 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agricultural Systems 143, 86-96

Casey, J., Holden, N., 2006a. Greenhouse gas emissions from conventional, agri-environmental scheme, and organic Irish suckler-beef units. Journal of Environmental Quality 35, 231-239

Casey, J., Holden, N., 2006b. Quantification of GHG emissions from sucker-beef production in Ireland. Agricultural Systems 90, 79-98

Charroin, T., Palazon, R., Madeline, Y., Guillaumin, A., Tchakerian, E., 2005. Le système d'information des Réseaux d'Elevage français sur l'approche globale de l'exploitation. Intérêt et enjeux dans une perspective de prise en compte de la durabilité. Renc. Rech. Rum 12, 335-338

Citepa, 2015. Rapport national d'inventaire pour la France au titre de la convention cadre des nations unies sur les changements climatiques et du protocole de Kyoto. Paris

Cohn, A.S., Mosnier, A., Havlík, P., Valin, H., Herrero, M., Schmid, E., O'Hare, M., Obersteiner, M., 2014. Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. Proceedings of the National Academy of Sciences 111, 7236-7241

Cournut, S., Chauvat, S., 2010. Référentiel travail dans 7 filières animales. Synthèse de 640 Bilans Travail bovins viande et lait, ovins viande et lait, caprins, porcs, volailles. In: Collection RMT travail. Institut de l'Elevage

Crosson, P., Shalloo, L., O'Brien, D., Lanigan, G.J., Foley, P.A., Boland, T.M., Kenny, D.A., 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Animal Feed Science and Technology 166–167, 29-45

De Cara, S., Jayet, P.-A., 2011. Marginal abatement costs of greenhouse gas emissions from European agriculture, cost effectiveness, and the EU non-ETS burden sharing agreement. Ecological Economics 70, 1680-1690

De Klein, C., Novoa, R.S., Ogle, S., Smith, K., Rochette, P., Wirth, T., McConkey, B., Mosier, A., Rypdal, K., Walsh, M., 2006. N2O emissions from managed soils, and CO2 emissions from lime and urea application. IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme 4, 1-54

Dong, H., Mangino, J., McAllister, T., Have, D., 2006. Emissions from livestock and manure management.

Esnouf, C., Russel, M., Bricas, N., 2011. duALIne-durabilité de l'alimentation face à de nouveaux enjeux. Questions à la recherche. Rapport Inra-Cirad

Eugène, M., Doreau, M., Lherm, M., Viallard, D., Oueslati, K., Faverdin, P., Sauvant, D., 2012. Projet « MONDFERENT » - Emissions de méthane par les bovins en France Rapport N° Programme 154 Action 14 Sous action 12

Fagon, J., Sabatté, N., 2010. Référentiel travail en élevages bovins lait. Synthèse de 190 Bilans Travail.

Foley, P.A., Crosson, P., Lovett, D.K., Boland, T.M., O'Mara, F.P., Kenny, D.A., 2011. Whole-farm systems modelling of greenhouse gas emissions from pastoral suckler beef cow production systems. Agriculture, Ecosystems & Environment 142, 222-230

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., 2007. Changes in atmospheric constituents and in radiative forcing. Chapter 2. In: Climate Change 2007. The Physical Science Basis.

Garnett, T., 2009. Livestock-related greenhouse gas emissions: impacts and options for policy makers. environmental science & policy 12, 491-503

Heckelei, T., Britz, W., 2005. Models based on positive mathematical programming: state of the art and further extensions. Modelling Agricultural Policies: State of the Art and New Challenges, Parma, Italy, 48-73

Idele, 2014. Quelle production française de viande bovine à l'horizon 2020 ? Dossier Economie de l'Elevage 450, 1-24

INRA, 2007. Alimentation des bovins, ovins et caprins: Besoins des animaux-Valeurs des aliments.ed QUAE, Paris, 307p

IPCC, 2007. Mitigation of climate change. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change

Janssen, S., van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: A review of bio-economic farm models. Agricultural Systems 94, 622-636

Johnson, J.M.F., Franzluebbers, A.J., Weyers, S.L., Reicosky, D.C., 2007. Agricultural opportunities to mitigate greenhouse gas emissions. Environmental Pollution 150, 107-124

Kanellopoulos, A., Berentsen, P., Heckelei, T., Van Ittersum, M., Lansink, A.O., 2010. Assessing the Forecasting Performance of a Generic Bio-Economic Farm Model Calibrated With Two Different PMP Variants. Journal of Agricultural Economics 61, 274-294

Kanellopoulos, A., Reidsma, P., Wolf, J., van Ittersum, M.K., 2014. Assessing climate change and associated socio-economic scenarios for arable farming in the Netherlands: An application of benchmarking and bio-economic farm modelling. European Journal of Agronomy 52, Part A, 69-80

Kentzel, M., 2010. Référentiel travail en élevages bovins viande. Synthèse de 170 Bilans Travail.

Koch, P., Salou, T., 2014. AGRIBALYSE®: METHODOLOGY, Version 1.1, March 2014. ADEME. Angers France pp 384

Lengers, B., Britz, W., Holm-Müller, K., 2013. Comparison of GHG-Emission Indicators for Dairy Farms with Respect to Induced Abatement Costs, Accuracy, and Feasibility. Applied Economic Perspectives and Policy 35, 451-475

Lengers, B., Britz, W., Holm-Müller, K., 2014. What Drives Marginal Abatement Costs of Greenhouse Gases on Dairy Farms? A Meta-modelling Approach. Journal of Agricultural Economics 65, 579-599

Lien, G., Hardaker, J.B., 2001. Whole-farm planning under uncertainty: impacts of subsidy scheme and utility function on portfolio choice in Norwegian agriculture. European review of agricultural economics 28, 17-36

Louhichi, K., Alary, V., Grimaud, P., 2004. A dynamic model to analyse the bio-technical and socio-economic interactions in dairy farming systems on the Reunion Island. Animal Research 53, 363-382

Mandryk, M., Reidsma, P., van Ittersum, M.K., 2012. Scenarios of long-term farm structural change for application in climate change impact assessment. Landscape Ecology 27, 509-527

Monteny, G.-J., Bannink, A., Chadwick, D., 2006. Greenhouse gas abatement strategies for animal husbandry. Agriculture, Ecosystems & Environment 112, 163-170

Mosnier, C., 2015. Self-insurance and multi-peril grassland crop insurance: the case of French suckler cow farms. Agricultural Finance Review 75, 533-551

Mosnier, C., Agabriel, J., Lherm, M., Reynaud, A., 2009. A dynamic bio-economic model to simulate optimal adjustments of suckler cow farm management to production and market shocks in France. Agricultural Systems 102, 77-88

Nerlove, M., Bessler, D.A., 2001. Expectations, information and dynamics. Handbook of agricultural economics 1, 155-206

Nguyen, T.T.H., Corson, M.S., Doreau, M., Eugène, M., van der Werf, H.M., 2013a. Consequential LCA of switching from maize silage-based to grass-based dairy systems. The International Journal of Life Cycle Assessment 18, 1470-1484

Nguyen, T.T.H., Doreau, M., Corson, M., Eugène, M., Delaby, L., Chesneau, G., Gallard, Y., Van der Werf, H., 2013b. Effect of dairy production system, breed and co-product handling methods on environmental impacts at farm level. Journal of environmental management 120, 127-137

Sauvant, D., Giger-Reverdin, S., Serment, A., Broudiscou, L., 2011. Influences des régimes et de leur fermentation dans le rumen sur la production de méthane par les ruminants. Productions Animales 24, 433

Sauvant, D., Nozière, P., 2016. Quantification of the main digestive processes in ruminants: the equations involved in the renewed energy and protein feed evaluation systems. Animal 10, 755-770

Schils, R., Olesen, J.E., Del Prado, A., Soussana, J., 2007. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livestock Science 112, 240-251

Simon, J., Le Corre, L., 1992. Le bilan apparent de l'azote al'echelle de l'exploitation agricole: methodologie, exemples de resultats. Fourrages

Soussana, J., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. animal 4, 334-350

Veysset, P., Lherm, M., Bébin, D., 2010. Energy consumption, greenhouse gas emissions and economic performance assessments in French Charolais suckler cattle farms: Model-based analysis and forecasts. Agricultural Systems 103, 41-50

Veysset, P., Lherm, M., Roulenc, M., Troquier, C., Bébin, D., 2015. Productivity and technical efficiency of suckler beef production systems: trends for the period 1990 to 2012. animal 9, 2050-2059

Zehetmeier, M., Baudracco, J., Hoffmann, H., Heißenhuber, A., 2012. Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. animal 6, 154-166

Appendix 1: Comparison of the model simulation to farm type references

	SC_GRASS			SC_CROPS			DC_GRASS			DC_CROPS		
	Ref[a]	B0	B'	***Ref***[b]	B0	B'	***Ref***[c]	B0	B'	***Ref***[d]	B0	B'
HERD SIZE (LSU)	***86***	85	*80*	***251***	246	*176*	**63**	63	50	**73**	72	71

MEAT PRODUCTION (KG /LSU)	309	292	300	384	384	393	na	210	176	na	178	175
MILK YIELD (L/COW)							5.7	5.6	6.0	7.8	7.8	7.9
MILK PRODUCTION (TONS)							200	200	200	390	390	390
STOCKING RATE (LSU/FORAGE AREA)	1.0	1.0	0.9	1.4	1.4	1.4	1.1	1.1	0.9	1.5	1.4	1.7
HARVESTED FODDER (TDM/LSU)	2.1	2.1	2.0	1.8	1.9	2.0	2.0	1.9	1.7	3.3	3.3	3.1
CONCENTRATE FEED (KG/LSU)	302	267	300	779	813	779	593	456	692	1080	1056	1356
CEREALS (HA)	0	0	0	67	67	101	0	0	0	11	11	14
OILSEEDS (HA)	0	0	0	35	35	51	0	0	0	0	0	9
SILAGE CORN (HA)	0	0	0	10	10	2	0	0	0	13	13	14
GRASSLANDS (HA)	87	87	87	168	168	126	55	60	34	37	37	24
N MINERAL (KG/HA)	15	17	8	70	82	92	50	60	34	66	71	54
FUEL (L/HA)	66	50	48	51	57	59	20	35	24	121	68	62
BEEF RECEIPTS (K€)	50	47	51	184	190	140	22	24	18	19	18	15
MILK RECEIPTS (K€)	0	0	0	0	0	0	69	71	69	134	134	110
CROP RECEIPTS (K€)	0	0	0	130	134	172	0	0	0	12	16	26
SUBSIDIES (K€)	44	44	44	103	103	98	15	15	15	21	21	21
VARIABLE COSTS (K€)	23	19	18	118	124	95	40	38	34	61	62	57
STRUCTURAL COSTS (K€)	33	34	34	123	119	125	31	28	27	53	48	44
DEPRECIATION COSTS (K€)	14	17	16	63	52	52	16	19	17	21	28	24
NET INCOME BEFORE SALARIES (K€)	21	19	23	104	130	135	17	24	23	46	51	47

[a] Réseaux d'élevage Auvergne-lozère, farm type BV10, 2010 : http://idele.fr/rss/publication/idelesolr/recommends/systemes-de-production-bovins-viande-du-bassin-rustique-sud-massif-central.html

[b] Réseaux d'élevage charolais, Farm type 31060, 2011: http://idele.fr/rss/publication/idelesolr/recommends/systemes-bv-du-bassin-charolais-actualisation-2011.html

[c] Réseaux d'élevage Normandie (vivre du lait en Normandie), Farm type 2, 2012: http://idele.fr/filieres/bovin-lait/publication/idelesolr/recommends/vivre-du-lait-en-normandie-2012.html

[d] Réseaux d'élevage Pays de la Loire, farm type 2B, 2011

B0 : Animal diets and crop operations are optimized for fixed levels of animal products and crop activities.
B': Crop allocation and herd size are optimized too for the average economic situation of 2008-2013, considering that building investments have been previously decided and that milk quotas are still enforced.

Appendix 2: Sensitivity analysis of production and GHG emission efficiency to beef and milk price

		Production in tons *(milk for dairy farms or meat for suckler cow farms)*				GHG emissions *(gross emissions /L or kg of meat)*			
		S1	S2	S3	S4	S1	S2	S3	S4
S C	1.15	24.2	24.8	22.9	16.1	14.3	14.3	13.4	14.4

	Beef	1	21.8	24.3	22.4	10.3	14.2	14.2	13.4	15.2
	price x	0.85	16.0	17.0	20.7		14.5	14.4	13.6	
SC_ Crops		1.15	81.9	97.5	83.7	52.4	13.3	13.2	13.1	13.1
	Beef	1	62.1	64.7	76.9	40.5	13.4	13.6	12.9	13.2
	price x	0.85	47.2	49.1	69.6	28.3	13.1	13.2	12.5	13.4
DC_ Grass		1.15	530	724	262	533	0.75	0.73	0.72	0.75
	Milk	1	525	707	251	508	0.75	0.73	0.72	0.75
	price x	0.85	487	551	213	329	0.75	0.75	0.72	0.75
DC_ Crops		1.15	609	974	336	600	0.65	0.66	0.70	0.65
	Milk	1	605	935	286	590	0.65	0.65	0.72	0.64
	price x	0.85	545	865	248	-	0.62	0.64	0.71	

Appendix 3: GHG emissions efficiency (CO_2e/L milk for dairy cows and CO_2e/kglw for suckler cow farms) **per scenarios according to two methodologies of calculation of enteric fermentation**

		B0	S1	S2	S3	S4
DC_Grass	CH4_Tier2[a]	0.84	0.79	0.79	0.71	0.79
	CH4_Sauvant[b]	0.94	0.85	0.84	0.77	0.85
DC_Crop	CH4_Tier2[a]	0.72	0.71	0.72	0.74	0.69
	CH4_Sauvant[b]	0.78	0.75	0.75	0.80	0.73
SC_Grass	CH4_Tier2[a]	12.5	11.8	11.9	11.3	12.0
	CH4_Sauvant[b]	13.9	13.2	13.3	12.5	13.9
SC_Crop	CH4_Tier2[a]	11.5	10.2	10.3	9.9	10.2
	CH4_Sauvant[b]	13.3	11.7	11.9	11.5	11.7

[a]Enteric fermentation calculated upon gross energy intake (Dong et al. 2006)

[b]Enteric fermentation calculated upon the digestible organic matter, taking into account digestive interactions (Sauvant et al. 2011)