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

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## 28 **Abstract**

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

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

## 50 **1. Introduction**

51 Paris Agreement (COP21, 2015) acknowledges the need to limit the temperature increase to 2 degrees  
52 Celsius to avoid the worst climate impacts. 188 countries have committed to reducing their greenhouse

53 gas (GHG) emissions and have set out a roadmap. The French low carbon national strategy targets a  
54 reduction of 12% of agricultural emission in 2028 relative to 2013 and of 50% between 1990 and 2050<sup>1</sup>.  
55 The agricultural sector contributes to 19% to national emissions (Citepa 2015). With a population of 19  
56 million of bovine, beef and dairy cattle productions are the main contributor to agricultural sector GHG  
57 emissions (60%). Evolution of the bovine sector in the next 20 years would be crucial to meet the GHG  
58 emissions target. This evolution would depend on numerous factors including technology, production  
59 organizations and markets, human population growth and consumer demand, climate change and policy.

60 The Gesebov project has investigated the joint evolution of the dairy and beef cattle sectors in horizon  
61 2035 and its associated level of GHG emissions at farm and national levels. The scenario approach is a  
62 widely used method to explore a highly uncertain future for agriculture (Abildtrup *et al.* 2006; Audsley  
63 *et al.* 2006; Mandryk *et al.* 2012) by describing coherent and plausible future states of the world. Since  
64 emissions of GHG by the bovine sector are first explained by the bovine inventory (Casey & Holden  
65 2006b) and second by the way meat and milk are produced (Monteny *et al.* 2006; Johnson *et al.* 2007),  
66 Gesebov scenarios have been specifically elaborated to be contrasted in terms of volume and technology  
67 of bovine production. The impacts of those scenarios on climate change were assessed at national level  
68 and at farm level. National level analysis provide estimates of beef, meat and GHG produced in France.  
69 Farm level analysis provide information regarding the potential evolution of heterogeneous farming  
70 systems (technical, economic and environmental). This paper focuses on the farm scale. Farm scale  
71 models enables to study relationships between production and GHG emissions per unit of product  
72 (Schils *et al.* 2007; Crosson *et al.* 2011). Bio-economic farm models can simulate impacts of new  
73 technologies or changes in the socio-economic environment on farming systems (Lien & Hardaker 2001;  
74 Louhichi *et al.* 2004; Janssen & van Ittersum 2007; Lengers *et al.* 2013; Kanellopoulos *et al.* 2014).

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

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<sup>1</sup> 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>

## 82 **2. Material and methods**

### 83 **2.1. Model description**

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

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

#### 97 **2.1.1. Cattle module**

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

107 Feed requirements are calculated on a monthly basis for each animal category to cover animal needs for  
108 maintenance and gestation, milk production and growth. Intake capacity, net energy and protein  
109 requirements are calculated thanks to the Inra methodology (INRA 2007). It provides flexibility to adapt  
110 diet composition to production contexts. Optimisation constraints impose that 1) energy and protein  
111 content of each animal diet (averaged monthly) meet animal needs, 2) fill value of animal diets equals  
112 their intake capacity (except at pasture where fill value could be 30% below intake capacity), 3) the

113 concentrate feed doesn't exceed a maximum value<sup>2</sup> and 4) feed could be available. Demographic  
114 constraints between animal categories enable to ensure that herd composition is balanced and respect  
115 the reproduction and ageing process.

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

## 120 **2.1.2. Crop module**

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

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

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<sup>2</sup> 30% except for dairy cow: 70% and during fattening periods: 50%

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

### 143 **2.1.3. Stable and machinery**

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

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

### 152 **2.1.1. Labor module**

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

### 164 **2.1.2. GHG emissions**

165 Thanks to a Life Cycle Assessment (LCA) approach, climate change impact associated with all the  
166 stages of an agricultural product's life from cradle to farm exit gate are assessed. Three gases contributes  
167 to global warming: methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>)

168 Methane emissions come from enteric fermentation and excreta of animals and are estimated with IPCC  
169 Tier2 or Tier 3 approach (Dong *et al.* 2006). Enteric methane emission factor (EF) is calculated  
170 according to Sauvant (Savant *et al.* 2011) using the equation 9<sup>6</sup> where EF is expressed in g CH<sub>4</sub>/kg  
171 DOM. DOM is the amount of Digestible Organic Matter ingested by the animal, calculated by the

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<sup>4</sup> [http://www.loiret.chambagri.fr/fileadmin/documents/Machinisme/Bareme\\_VITI\\_ARBO\\_Edition\\_2013.pdf](http://www.loiret.chambagri.fr/fileadmin/documents/Machinisme/Bareme_VITI_ARBO_Edition_2013.pdf)

<sup>5</sup> [http://www.bourgogne.chambagri.fr/uploads/media/plaquette\\_Le\\_travail\\_en\\_%C3%A9levage\\_laitier\\_01.pdf](http://www.bourgogne.chambagri.fr/uploads/media/plaquette_Le_travail_en_%C3%A9levage_laitier_01.pdf)

<sup>6</sup> Also reported in (Savant & Nozière 2016) eq 48

172 product of the amount of organic matter ingested (OM, kg) by OM digestibility (dOM) of the diet. This  
173 latter is equal to the average dMO of diet with three corrective parameters<sup>7</sup> to take into account digestive  
174 interactions (Sauvant & Nozière 2016): the quantity of dry matter intake per unit of live weight  
175 (DMI%LW), the amount of concentrate feed (CO) and the rumen protein balance (RPB). EF is a second  
176 degree polynomial function involving DMI%LW and CO in animal diet. Globally, this emission factor  
177 decreases when the quantity of dry matter intake per kg of live weight increases and when the amount  
178 of concentrate feeds exceeds 30%. To estimate methane from dejections, we use IPCC equation  
179 10.23(Dong *et al.* 2006). Following Eugène *et al.* (2012), the daily volatile solid excreted is estimated  
180 by the non-digestible organic matter ingested by animals which is the difference between total organic  
181 matters ingested and the digestible organic matter ingested. Urine components of volatile solid were  
182 assumed negligible.

183 Nitrous emissions are divided into direct emissions from manure management and managed soils and  
184 indirect N<sub>2</sub>O emissions that arise from volatilization of fertilizers, and nitrogen (N) lost via runoff and  
185 leaching from agricultural soils. N<sub>2</sub>O emissions from manure management systems, calculated  
186 according to IPCC Tier2- Tier 3 (Dong *et al.* 2006), are proportional to the quantity of N excreted by  
187 animals. N excretion is calculated for each animal activity and month by the difference between N  
188 ingested *via* conserved feed or fresh grass and N fixed by meat and milk (equation 10.33). N excretion  
189 is then allocated to the different manure management systems according to the time spent in a given  
190 barn or paddock. Direct emissions of N<sub>2</sub>O from managed soils are computed according to IPCC Tier 1  
191 (De Klein *et al.* 2006). They take into account manure spreading and inorganic N fertilization, annual  
192 amount of N in crop residues and from pasture renewal and the annual amount of urine and dung N  
193 deposited by grazing animals on pasture. Indirect N<sub>2</sub>O emissions has been estimated based on the  
194 nitrogen balance calculated on a farm scale (Simon & Le Corre 1992).

195 Indirect CO<sub>2</sub> emissions of inputs purchased are estimated thanks to Dia'terre methodology (ADEME  
196 2010). CO<sub>2</sub> may be emitted from or sequestered into agricultural soils. Assumptions made here rely on  
197 (Soussana *et al.* 2010). We suppose that permanent grasslands store 570 kg C/ha/yea, annual crops  
198 destock 160 kg C/an/year, temporary grasslands store 570 kg C/ha/an and then destock 950 kg/year the  
199 two years following grassland destruction. Note that CO<sub>2</sub> emissions from liming and urea fertilization  
200 have not been accounted for since these operations have not been introduced in the set of crop operations.

201 The three gases are aggregated by their potential of global warming into a single indicator expressed in  
202 CO<sub>2</sub> equivalent (CO<sub>2</sub>e). Values are those proposed by IPCC ((Forster *et al.* 2007), p212, 100-year time  
203 horizon): CO<sub>2</sub> =1; CH<sub>4</sub> = 25; N<sub>2</sub>O = 298. Emissions are computed at farm level and by unit of animal

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<sup>7</sup> equation 24

204 product. To estimate net impact of livestock production on climate change the quantity of carbon stored  
 205 (net CO<sub>2</sub>e) in soils have been deducted from total emissions.

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

### 212 2.1.3. Objective function

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

### 218 2.1. Case studies

219 Four farm types have been selected within the Inosys-Réseaux d'élevage referential<sup>8</sup> (Charroin *et al.*  
 220 2005) to cross cattle production orientation with land characteristics: a dairy farm with permanent  
 221 grassland only (DC\_Grass) in Normandy (oceanic climate north-west of France), a dairy farm with  
 222 temporary grasslands and annual crops (DC\_Crops) in Pays de la Loire (west of France), a suckler cow  
 223 farm with permanent grasslands only (SC\_grass) in the mountains of Cantal (south Massif Central centre  
 224 of France), and a suckler cow farm fattening young bulls with grasslands and annual crops (SC\_Crops)  
 225 in the North of Massif Central (table 1). Further details are provided in Appendix 1.

226 **Table 1: Main characteristics of the farm types selected**

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

<sup>8</sup> 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

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

## 228 2.2. Scenarios

229 Two kinds of scenarios have been developed. The trend scenario (**S1**) is considered as the most probable  
230 from the 2014 perspective. It has been elaborated considering past trends and the most likely evolution  
231 of technology and markets (Idele 2014). Alternatives scenarios have been constructed by expert groups  
232 gathering people working in the beef and dairy sectors and researchers, to explore other plausible futures  
233 (table2). For the trend scenario **S1**, it is assumed that at national level dairy production would increase  
234 taking advantage of new opportunities to export while suckler beef production (-11% of suckler cows)  
235 would shrink because of a reduction in outlets for exports and an increase of beef produced by the dairy  
236 herd. Scenario **S2** assumes an expansion of beef and above all dairy production to meet the raising global  
237 world demand. Farm enlargement would be accompanied by a high increase in labor efficiency and a  
238 high level of mechanization (without additional costs thanks to the high level of diffusion of  
239 technological progress). The scenario **S3** considers the opposite situation with the development of a  
240 local environmentally friendly production based on grasslands with double purpose breeds (Normande,  
241 Montbeliarde). It is associated to a decrease in the quantity of beef and milk produced and consumed.  
242 Eventually, the scenario **S4**, depicts a situation where the reduction of GHG emission is a priority and  
243 is enforced by a proactive policy and by a growing vegetarian population. These scenarios are compared  
244 to the baseline scenario **B0** which reproduces the farming systems for the average economic situation of  
245 2008-2013.

246 **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 -/+
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247  
 248 The main technological progresses and socio-economic drivers of the scenarios were selected to  
 249 simulate their effects at farm level (table 3). In order to facilitate the interpretation of results, a voluntary  
 250 limited number of factors have been modified between scenarios.

251 A set of new technologies is proposed for all 2035 scenarios (S1-S4). These technologies can be adopted  
 252 or not according to farm type and scenarios (decision is endogenous). Holstein Friesian dairy cows with  
 253 higher milk potential (10000L/cow max.) are proposed in addition to the actual Holstein Friesian (8000  
 254 L/ cow) and Normande breed (6000 L/cow). Milk yield is indeed expected to rise but genetic potential  
 255 improvement would slow down in the future (+25%) compared to past trends (+50% in average between  
 256 1990 and 2010). 10 000 L-milk-yield cows are supposed to be fed indoors only because of the high  
 257 energy content of their diet. They are also slightly heavier (+3.5%) in order to have an intake capacity  
 258 compatible with their requirements. Although carcasses have enlarged over the past (+13% between  
 259 1990 and 2013 (Veysset *et al.* 2015)), according to experts heavy carcasses don't meet anymore the  
 260 market demand. Consequently, we assume constant carcass weight for beef breeds. Given practices  
 261 currently observed in other countries, first calving would be possible three months younger for beef and  
 262 dairy breeds in 2035. The fertilization efficiency has progressed a lot during the past decades in the  
 263 studied systems (at least -20% of mineral nitrogen fertilization between 1990 and 2010) and would  
 264 continue to progress but at a smaller rate (10% less of nitrogen is required for the same average yield in  
 265 2035). Eventually, legume fodder and mixture of cereal and protein crops are supposed to be accessible  
 266 everywhere land is tillable. Regarding prices, milk, beef and cereal prices are set at baseline for scenarios  
 267 S1 to S4 (average over the period 2008-2013). A sensitivity analysis of the results to beef and dairy  
 268 prices are nonetheless provided in *appendix 2* given uncertainties related to milk and beef prices. Similar  
 269 to Kanellopoulos et al (2014), fuel and fertilizers prices are assumed to increase by 40%. Regarding  
 270 policy, simulations are made without subsidies. We know that the current CAP policy will be reformed  
 271 but we don't make hypothesis on the issues of future negotiations.

272 Differences between scenarios arise from the doubling of labor productivity in **S2** (more than +100%  
 273 were observed between 1990 and 2010 (Veysset *et al.* 2015)). This implies both a reduction of  
 274 production cost and an increase of the production capacity since labor is a limiting resource on the farm.  
 275 In **S3**, we test the obligation to produce organic products with not more than 10% of concentrate feed in  
 276 the total dry matter intakes. Similar to the current French situation, organic prices are 20% higher of  
 277 milk and 15% higher for animals ready to be slaughtered. Eventually, a tax on carbon net emissions,  
 278 equal to 40€/t CO<sub>2</sub>e, is enforced in **S4**. This value is in line with assumptions used in several studies  
 279 (IPCC 2007; De Cara & Jayet 2011).

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

288 **Table 3: Summary of assumptions in the simulated scenarios**

<b>B0</b>	Baseline price (average 2008-2013)
<b>S1-S4</b>	- 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%)
<b>S2</b>	Labor productivity x2
<b>S3</b>	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 )
<b>S4</b>	Tax on net carbon emission (40€/ t)

## 289 3. Results

### 290 3.1. Global GHG emission and production at farm level

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

295 In the trend scenario **S1**, milk production is multiplied by 1.5 in the dairy cow farm with annual crops  
 296 (DC\_Crops) (figure 1). It increases even more in DC\_Grass (x2.5) which specializes in milk production  
 297 and switches dual-purpose Normande cows for more productive Holstein Friesian ones. Because of the  
 298 highest increase in milk yield, meat production augments in smaller proportion in DC\_Grass (+12%)  
 299 than in DC\_Crops (+23%). Regarding suckler cow farms, meat production decreases (-8% in SC\_Grass  
 300 and -35% in SC\_Crops). Temporary grasslands are replaced by cash crops in SC\_Crops (figure 3). In  
 301 the case of DC\_Crops, oilseeds, alfalfa and the mixture of cereals and protein crops expand at the  
 302 expense of temporary grasslands. Total **gross GHG emissions** are multiplied by 1.6, 1.3, 1.1 and 1 in  
 303 DC\_Grass, DC\_Crops, SC\_Grass and SC\_Crops, respectively. Change in **net emissions** are particularly

304 important in DC\_Grass since sequestration compensates 41% of gross emissions in the baseline but only  
 305 26% in S1 (stocking rate increases).

306 In scenario **S2**, the gain in labor efficiency reduces production costs and allows more cows or cash crops  
 307 per worker unit. Cattle production increases slightly in suckler cow farms (+7% for DC\_Grass; +4% for  
 308 SC\_Crops relative to S1) and strongly in dairy farms (+33% for DC\_grass; +57% for DC\_Crops). All  
 309 crops grown on DC\_crops are used to feed animals while SC\_Crops maintains the maximum area with  
 310 cash crops. Total **gross GHG emissions** are multiplied respectively by 1.3, 1.6, 1 and 1.1 relative to S1  
 311 in DC\_Grass, DC\_Crops, SC\_Grass and SC\_Crops.

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

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

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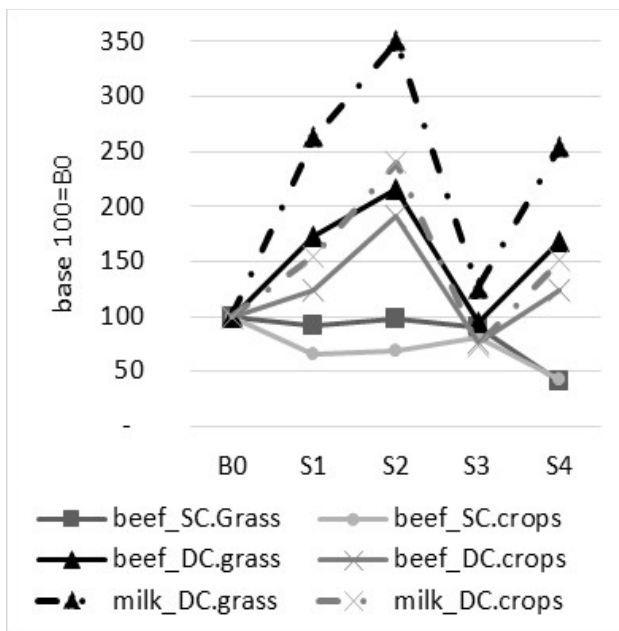


Figure 1 : Evolution of beef and milk production per farm

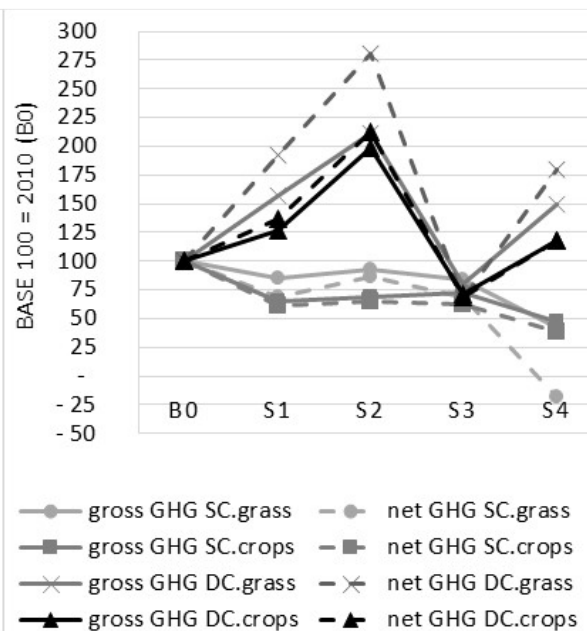
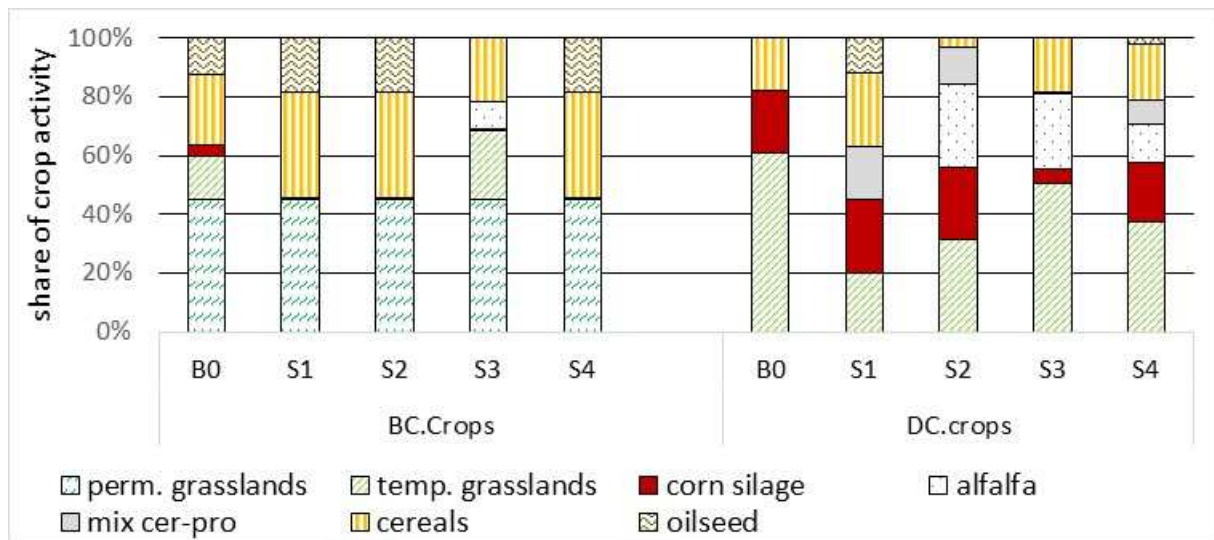


Figure 2 : Evolution of gross and net GHG emissions per farm

324



325

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

### 327 3.2. GHG emission efficiency and production technology

328 **For suckler cow farms**, gross GHG emissions per kg of live meat decreases between 4% and 10% in  
 329 **S1** relative to B0. This benefit could be first attributed to younger first calving ( $\approx -0.5$  kg CO<sub>2</sub>e /kgLW<sup>9</sup>).  
 330 Early calving raises meat production per LSU (between +3% and +5% relative to B0) with counterpart  
 331 a slight increase in organic matter ingested to meet higher feed requirements of female heifers. A higher  
 332 share of liquid manure in total manure production in SC\_Crops (25% instead of 0% in B0) decreases  
 333 N<sub>2</sub>O and CH<sub>4</sub> emissions linked to manure management (cows are housed in cubicles with a liquid  
 334 manure system). Spring calving instead of winter calving for SC\_Crops (winter calving is retained in  
 335 SC\_Grass) and a better optimization of the system explain also these gains. GHG emissions in **S2** are  
 336 rather similar to S1 since the production system is little impacted by the increase in labor efficiency. In  
 337 **S3**, animal diets are significantly modified (figure 4). The introduction of grass silage reduces slightly  
 338 CH<sub>4</sub> emissions for SC\_Grass; the partial substitution of concentrate feed by green fodder and alfalfa  
 339 increases CH<sub>4</sub> emissions for SC\_Crops. Nonetheless, the reduction of the consumption of concentrate  
 340 feeds and purchased fertilizer enable to reduce GHG emissions per kg of meat up to 5% relative to S1  
 341 and up to 14% relative to B0. **In S4**, beef production per hectare becomes very low in SC\_Grass (0.5  
 342 LSU/ha), probably too low to prevent the emergence of shrubs. Gross emissions per kg of meat  
 343 deteriorates because of weanlings sold younger. Net emissions become negative because carbon storage  
 344 more than offsets GHG emissions.

<sup>9</sup> Additional simulations have been run to isolate effects of each ‘technological progress’

345 **For dairy farms**, emissions per kg of milk decrease significantly in **S1** for DC\_Grass (-16% in S1  
346 compared to B0) and to a lesser extent for DC\_Crops (-10% in S1 compared to B0). These gains are  
347 first obtained through an increase in milk yield. DC\_Grass switches Normande for Holstein Friesian  
348 cows (average milk yield=8970 L/ cow, +61% relative to B0) and DC\_Crops benefits from the increase  
349 in milk potential of Holstein Friesian (average milk yield= 9735 L/cow, +24%). It reduces enteric  
350 fermentation per milk unit (enteric CH<sub>4</sub>: -30% for DC\_Grass, -15% for DC\_Crops) and N excretion per  
351 milk unit. The calving period chosen is spring. Younger first calving which is always chosen whatever  
352 the farm and scenario and the heaviest carcass of Holstein Friesian in the case of dairy farms (+3.5%)  
353 raises meat production and reduces GHG emissions per kglw (table 4). Because of the intensification of  
354 animal production per hectare in DC\_Crops (from 1.4 to 2.2 LSU/ha), the share of grass based fodder  
355 shrinks while concentrate feed (30% of total DM intake) and crop fodders (corn, mix cereal-protein and  
356 alfalfa) take more importance in animal diets (figure 4). In **S2**, the gain in animal productivity is little  
357 and production intensifies per hectare. The consumption of feed concentrate is more important for all  
358 animal categories. GHG emissions allocated to beef increase significantly. In **S3**, milk yield strongly  
359 decreases (average milk yield: 6.5 tons of milk per cow in DC\_Grass; 6 tons/cow in DC\_Crops) because  
360 of the organic constraint and above all the limitation of feed concentrate consumption (< 10% of total  
361 DM intake). Stocking rates decrease and diets are based principally on grassland products and alfalfa.  
362 The increase in methane emission per liter of milk is partly offset by a reduction of CO<sub>2</sub> emissions for  
363 DC\_Crops and more than offset for DC\_Grass. Net emissions are reduced per liter of milk and meat. In  
364 **S4**, production systems are rather comparable to the trend scenario except that, in DC\_Crops purchased  
365 concentrates decrease and alfalfa increases at the expense of corn silage. Emissions are lower than in  
366 B0.

367 **Table 4: GHG emissions of suckler cow farms in kg CO<sub>2</sub>e/kg of liveweight**

	B0	S1	S2	S3	S4	
SC_Grass	CO <sub>2</sub>	1.29	1.05	1.14	0.71	1.10
	CH <sub>4</sub>	9.86	9.71	9.63	9.58	9.81
	N <sub>2</sub> O	3.63	3.43	3.46	3.13	4.28
	<b>Gross CO<sub>2</sub>e</b>	<b>14.8</b>	<b>14.2</b>	<b>14.2</b>	<b>13.4</b>	<b>15.2</b>
	<b>Net CO<sub>2</sub>e</b>	<b>7.28</b>	<b>5.69</b>	<b>6.48</b>	<b>5.34</b>	<b>-3.23</b>
SC_Crops	CO <sub>2</sub>	1.70	1.34	1.42	0.84	1.12
	CH <sub>4</sub>	8.83	8.37	8.37	8.60	8.55
	N <sub>2</sub> O	4.51	3.67	3.79	3.39	3.57
	<b>Gross CO<sub>2</sub>e</b>	<b>15.0</b>	<b>13.4</b>	<b>13.6</b>	<b>12.9</b>	<b>13.2</b>
	<b>Net CO<sub>2</sub>e</b>	<b>12.2</b>	<b>10.1</b>	<b>10.4</b>	<b>9.1</b>	<b>8.8</b>

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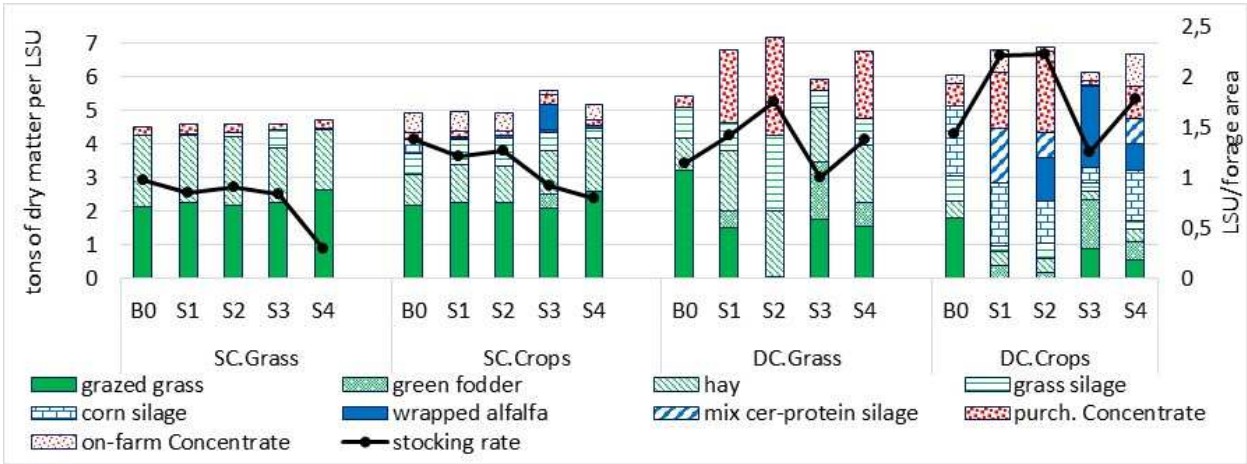
369 **Table 5: GHG emissions in dairy farms (in kg CO<sub>2</sub>e/kg of liveweight or per kg of milk )**

	kg CO <sub>2</sub> e/kg liveweight					kg CO <sub>2</sub> e /kg Milk				
	B0	S1	S2	S3	S4	B0	S1	S2	S3	S4

DC_grass	<i>CO</i> <sub>2</sub>	1.35	1.95	2.95	0.74	1.81	0.09	0.17	0.19	0.02	0.17
	<i>CH</i> <sub>4</sub>	7.05	4.75	4.38	6.50	4.77	0.58	0.46	0.44	0.58	0.46
	<i>N</i> <sub>2</sub> <i>O</i>	3.41	2.44	2.64	3.03	2.34	0.22	0.13	0.11	0.12	0.12
	Gross CO <sub>2</sub> e	<b>11.8</b>	<b>9.13</b>	<b>9.97</b>	<b>10.5</b>	<b>8.88</b>	<b>0.89</b>	<b>0.75</b>	<b>0.73</b>	<b>0.72</b>	<b>0.75</b>
	Net CO <sub>2</sub> e	<b>7.31</b>	<b>6.91</b>	<b>8.17</b>	<b>5.51</b>	<b>6.61</b>	<b>0.55</b>	<b>0.57</b>	<b>0.60</b>	<b>0.38</b>	<b>0.56</b>
DC_crops	<i>CO</i> <sub>2</sub>	0.87	1.61	2.22	0.45	1.31	0.11	0.13	0.14	0.03	0.11
	<i>CH</i> <sub>4</sub>	5.71	4.67	4.28	5.26	4.71	0.49	0.44	0.44	0.59	0.44
	<i>N</i> <sub>2</sub> <i>O</i>	2.69	2.17	2.16	2.28	2.12	0.13	0.08	0.08	0.11	0.09
	Gross CO <sub>2</sub> e	<b>9.26</b>	<b>8.46</b>	<b>8.67</b>	<b>8.04</b>	<b>8.15</b>	<b>0.73</b>	<b>0.66</b>	<b>0.65</b>	<b>0.73</b>	<b>0.65</b>
	Net CO <sub>2</sub> e	<b>8.52</b>	<b>8.34</b>	<b>8.50</b>	<b>7.20</b>	<b>7.48</b>	<b>0.68</b>	<b>0.65</b>	<b>0.64</b>	<b>0.65</b>	<b>0.60</b>

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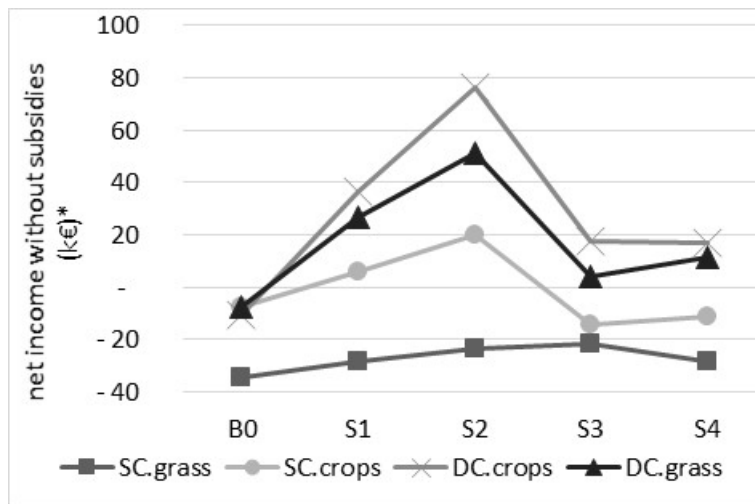


372

373 **Figure 4: Quantity of feed in animal diets**

### 374 3.3. Economic results

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



385

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

## 387 4. Discussion

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

### 397 4.1. Validity of the farm model simulations

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

- 401 • Simulation of the production processes and farmers' decisions

402 Some calibrating method, such as Positive Mathematical Programming are often used to reproduce  
 403 exactly the observed production decisions in adjusting automatically the production costs of the different  
 404 farm activities (Heckelei & Britz 2005; Kanellopoulos *et al.* 2010). Nonetheless this method gets very  
 405 complicated when activities are highly embedded, especially with animal production, and is not relevant  
 406 for long term simulation in which technology could change drastically (Kanellopoulos *et al.* 2014). We  
 407 opted instead for a calibration/ validation in two steps: 1) animal diets and crop operations were



408 optimized for fixed levels of animal products and crop activities; 2) Crop allocation and herd size were  
409 also optimized for the average economic situation of 2008-2013, considering that building investments  
410 have been previously decided (short term optimization) and that milk quotas are still enforced. Technical  
411 and economic model outputs were compared to farm type referential from Inosys Réseaux-d'élevage  
412 (Charroin *et al.* 2005). When crop and animal activities were fixed (Appendix 1), we observe a good  
413 match for feed, fuel and fertilizer consumption and close economic results.

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

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

- 437 • Validity of GHG emissions indicators

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

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<sup>10</sup> 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)

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

#### 453 **4.2. Are possible evolutions of cattle farms compatible with climate change** 454 **mitigation objectives?**

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

456 Higher milk yield and younger age at first calving were chosen in almost all scenarios and farm types  
457 (except for milk yield in scenario S3). It enabled to reduce significantly methane emissions. As enteric  
458 methane is a leading source of GHG emissions, a strategy often put forward is indeed to increase the  
459 ratio of livestock ‘production’ to ‘maintenance’ thanks to faster growth, higher milk yields or shorter  
460 dry periods lactating cows (Monteny *et al.* 2006). Feed intake increases usually with energy  
461 expenditures. Nonetheless, the rumen activity is modified by larger diets and by diets with higher share  
462 of concentrate feeds, leading to a reduction of CH<sub>4</sub> emissions per unit of product (Monteny *et al.* 2006).  
463 The indirect CO<sub>2</sub> emissions linked to the consumption of concentrate feeds partly offset the reduction  
464 of methane emissions. It explains why organic farming associated to a low level of feed concentrate  
465 (scenario 3) presents the lowest emission per output unit for suckler cow systems and for dairy  
466 production based on grasslands. We also show that legume fodders can limit the increase of indirect  
467 CO<sub>2</sub> emissions induced by an intensification of the forage area. Taking into account carbon sequestration  
468 in grasslands, scenarios 3 and 4 (tax on GHG emissions) brings the best results in terms of net GHG  
469 emission efficiency.

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

475 2010), moderate intensification (Foley *et al.* 2011) or organic farming systems in Ireland (Casey &  
476 Holden 2006a) appear as a valuable alternative to reduce GHG emissions per unit of meat. In dairy  
477 production, Nguyen *et al.* (2013b) estimate that more intensive French dairy production systems emit  
478 less GHG per milk unit while New-Zealand studies point that, for a given level of milk production per  
479 animal, milk production intensification per hectare reduces GHG emission efficiency (Basset-Mens *et*  
480 *al.* 2009; Adler *et al.* 2015). Gains obtained thanks to the intensification of the production systems are  
481 not linear and beyond a certain level of intensification, an increase in fertiliser use and concentrate feed  
482 consumptions offset the reduction of methane emissions.

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

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

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

500 We simulated that GHG emissions, milk and beef production from dairy farms are likely to increase in  
501 all scenarios, except S3, and that GHG emissions and beef production from suckler cow farms are likely  
502 to decrease, especially if a tax on GHG emissions is introduced. Sensitivity analysis also emphasizes  
503 that cattle productions from farms with tillable lands are more sensitive to prices since they have more  
504 room to intensify their cattle production if the prices are good or otherwise to switch to annual cash crop  
505 production. This findings are globally in line with assumptions made at France level. At France level,  
506 the trend scenario projects an increase of beef and above all milk productions from dairy farms, mainly  
507 in north-west France and a reduction of beef production from suckler cow systems that would be  
508 maintained primarily on permanent grasslands. Milk and beef are interlinked. Zehetmeier *et al* (2012)  
509 demonstrate that if we need more suckler cow to compensate the reduction of the number of dairy cows,

510 this may downgrade the GHG performance of the global bovine sector. Nonetheless it was assumed that  
511 milk surplus would be exported, thus the global performance of the bovine sector is maintained.  
512 Nonetheless, according to export-import scenarios, more or less milk and beef would be produced  
513 elsewhere, modifying the carbon footprint at global level. This underlines the necessity to analyse the  
514 milk and beef carbon footprint worldwide (Garnett 2009; Nguyen *et al.* 2013a; Cohn *et al.* 2014). In  
515 addition, our scenarios assume changes in per capita food consumptions. Scenarios 3 and above all 4  
516 hypothesise a reduction in beef and milk consumption. According to Esnouf *et al.* (2011), a reduction  
517 of the consumption of animal products may induce an increase of vegetable food that would *in fine* have  
518 negative impact on global GHG emissions. The assessment of scenarios should then be extended to  
519 other agricultural products (cereal, vegetables, etc.). Other dimensions should also be accounted for  
520 since these scenarios could have major impacts on water and air quality (manure surplus, dust),  
521 biodiversity (namely in grasslands), rural development (employment, equal development between  
522 territories) or resilience.

## 523 **5. Conclusion**

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

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

541 Nonetheless, impacts of these scenarios have been analyzed only partially. First, only a limited number  
542 of mitigation options have been introduced in this study, focusing on production intensification or  
543 extensification. Second, other dimensions -including air and water quality, biodiversity, energy

544 consumption, rural development and employment and resilience of the farming systems- should be taken  
545 into account at farm and territorial levels to assess which scenario may be suitable. Eventually, this  
546 study should be complemented by an analysis at global scale, including other agricultural sectors and  
547 taking into account the evolution of human diets.

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

	SC_GRASS			SC_CROPS			DC_GRASS			DC_CROPS		
	<i>Ref<sup>a</sup></i>	B0	B'	<i>Ref<sup>b</sup></i>	B0	B'	<i>Ref<sup>c</sup></i>	B0	B'	<i>Ref<sup>d</sup></i>	B0	B'
<b>HERD SIZE (LSU)</b>	<b>86</b>	85	80	<b>251</b>	246	176	<b>63</b>	63	50	<b>73</b>	72	71

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

- 684 <sup>a</sup> Réseaux d'élevage Auvergne-lozère, farm type BV10, 2010 :  
685 <http://idele.fr/rss/publication/idelesolr/recommends/systemes-de-production-bovins-viande-du-bassin-rustique-sud-massif-central.html>  
686  
687 <sup>b</sup> Réseaux d'élevage charolais, Farm type 31060, 2011:  
688 <http://idele.fr/rss/publication/idelesolr/recommends/systemes-bv-du-bassin-charolais-actualisation-2011.html>  
689 <sup>c</sup> Réseaux d'élevage Normandie (vivre du lait en Normandie), Farm type 2, 2012:  
690 <http://idele.fr/filieres/bovin-lait/publication/idelesolr/recommends/vivre-du-lait-en-normandie-2012.html>  
691 <sup>d</sup> Réseaux d'élevage Pays de la Loire, farm type 2B, 2011

692 *B0 : Animal diets and crop operations are optimized for fixed levels of animal products and crop activities.*

694 *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.*

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## 700 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
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	

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702 **Appendix 3: GHG emissions efficiency (CO<sub>2</sub>e/L milk for dairy cows and CO<sub>2</sub>e/kgLW for suckler cow**  
703 **farm) per scenarios according to two methodologies of calculation of enteric fermentation**

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

704 <sup>a</sup>Enteric fermentation calculated upon gross energy intake (Dong et al. 2006)

705 <sup>b</sup>Enteric fermentation calculated upon the digestible organic matter, taking into account digestive  
706 interactions (Sauvant et al. 2011)

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