

Scotland's Rural College

## Identifying cost-competitive greenhouse gas mitigation potential of French agriculture

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# 1 Identifying cost-competitive greenhouse gas mitigation potential of French 2 agriculture

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37

38

39 **Abstract**

40

41 The agriculture, forestry and other land use sector is responsible for 24% (10-12 Pg CO<sub>2</sub>e per  
42 year) of anthropogenic greenhouse gas (GHG) emissions worldwide, with concomitant  
43 opportunities for mitigation. A scientific panel used deliberative methods to identify ten  
44 technical measures comprising 26 sub-measures to reduce GHG emissions from agriculture in  
45 France. Their abatement potential and cost are compared. The proposed measures concern  
46 nitrogen (N) management, management practices that increase carbon stocks in soils and  
47 biomass, livestock diets, and energy production and consumption on farms. Results show that  
48 the total abatement potential can be divided into three parts. One third of the cumulated  
49 abatement potential corresponds to sub-measures that can be implemented at a negative  
50 technical cost. These sub-measures focus on increased efficiency in input use including N  
51 fertilisers, animal feed and energy. The second third are sub-measures with moderate cost (<  
52 €25 per metric Mg of avoided CO<sub>2</sub>e). These sub-measures require specific investments or  
53 changes to cropping systems, but additional costs or lower incomes are partially compensated  
54 for by a reduction in other costs or by the production of other marketable products. The  
55 remaining third are high-cost sub-measures (> €25 per metric Mg of avoided CO<sub>2</sub>e). These  
56 require investment with no direct financial return, the purchase of particular inputs, dedicated  
57 labour time or involve production losses. Assuming additivity, the cumulated abatement is  
58 32.3 Tg CO<sub>2</sub>e per year in 2030, but only 10 Tg (i.e. 10% of current agricultural emissions)  
59 when calculated under current inventory rules. This study confirms that a significant  
60 abatement potential exists in the agricultural sector, with two thirds of this potential at low or  
61 even negative cost. This is likely to be an underestimated as it is based on a status quo of the  
62 current agricultural system. Results also emphasise the need to upgrade inventory rules so that  
63 efforts to reduce emissions can be accounted for.

64

65 **Keywords**

66

67 Greenhouse gas, agriculture, mitigation measures, marginal abatement costs

68

69

## 70 1. Introduction

71  
72 Agriculture, forestry and other land use (AFOLU) is responsible for 24% (10-12 Pg CO<sub>2</sub>e per  
73 year) of greenhouse gas (GHG) emissions worldwide (Smith et al., 2014). Of this, 12% is  
74 caused by land use and land use changes, including deforestation and draining peat, mainly as  
75 CO<sub>2</sub>; 7% is due to methane (CH<sub>4</sub>) produced by ruminants and by anaerobic fermentation of  
76 organic matter, especially in saturated soils such as paddy fields; and 5% is due to nitrous  
77 oxide (N<sub>2</sub>O) produced by biochemical nitrification and denitrification reactions in soils and  
78 manures. One particular feature of agricultural emissions is that they are mainly not related to  
79 energy but are controlled by diffuse biological processes.

80  
81 Agriculture can contribute to international and national GHG reduction objectives using three  
82 levers: reducing N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> emissions, storing more carbon in soil and biomass and  
83 producing bioenergy (biofuels, biogas) to replace fossil energies, thereby reducing emissions  
84 by a substitution effect. Many mitigation measures have been proposed at the global scale or  
85 for specific countries, agricultural sectors or gases, sometimes associated with rough estimates  
86 of their abatement potential (e.g. Cole et al., 1997; Smith et al., 2008, 2013 at the global scale;  
87 Aertsens et al., 2013 at the continental scale; Schneider et al., 2007; Fitton et al., 2011; Rees  
88 et al., 2013 at the national scale; Monteny et al., 2006; Schils et al., 2013 for the livestock  
89 sector; Sommers and Bossio, 2014 for organic carbon storage in soils; Zomer et al., 2016 for  
90 agroforestry). However, because of the mainly diffuse nature of the emissions, the complexity  
91 of the underlying biophysical and behavioural processes and the huge variability of  
92 production systems, the potential for abatement is less precisely quantified in the agricultural  
93 sector than in other sectors. Yet, for policy-making purposes, it is essential to accurately  
94 assess and compare the cost of the numerous available levers.

95  
96 Vermont and De Cara (2010) identified three main approaches to assess mitigation costs and  
97 abatement potentials: (i) top-down economic models representing the functioning of the  
98 agricultural sector and markets at the global scale and at a country/regional resolution, (ii)  
99 supply-side sector micro-economic models based on representative farms, and (iii) bottom-up  
100 approaches assessing the potential and costs of a set of individual mitigation measures or  
101 practices. The two first approaches focus on the impacts of a carbon price on abatement  
102 potential, whereas the latter approach enables a more detailed or “engineering” assessment of  
103 technological mitigation measures. A typical output of these studies is a marginal abatement  
104 cost curve (MACC), which ranks the measures or practices by increasing mitigation cost  
105 along with their mitigation potential. Examples of the use of this approach in a number of  
106 national contexts can be found in MacLeod et al., 2010; Moran et al., 2011 for the UK;  
107 O’Brien et al., 2014 for Ireland; Wang et al., 2014 for China. Bottom-up engineering are  
108 typically based on a two-step process, first, screening candidate measures to select the most  
109 relevant ones in the agricultural context concerned, and second, detailed calculations of their  
110 potential abatement and cost. Existing studies are limited in that they often consider both  
111 short-term technical options which can be implemented immediately, like fertilisation or  
112 tillage management practices, and long-term levers that require further investments and  
113 research, like crop or animal breeding based on new selection criteria. Considering all  
114 categories of measures together may be confusing for policy making purposes since they do  
115 not use the same time scales or address the same end-users. Moreover, in addition to the  
116 challenges of calculating abatement potential and costs, O’Brien et al. (2014) pointed out that  
117 the outcomes of such studies are highly dependent on the method used to calculate the  
118 abatement, i.e. the IPCC-national inventory approach or a life cycle assessment approach.  
119 Most studies use the IPCC-national inventory approach, so that the proposed mitigation

120 options to reduce emissions from the national agricultural sector may inadvertently increase  
121 global emissions because of the effects they have elsewhere in the world (Franks and  
122 Hadingham, 2012). Therefore, a clear distinction must be made between direct emissions  
123 (occurring on the farm), indirect emissions (occurring outside the farm, after physical transfer  
124 of molecules) and emissions induced upstream or downstream of the farm, through the  
125 purchase or sale of goods or services.

126  
127 This study compares the abatement potential and cost of technical measures designed to  
128 reduce GHG emissions from the agricultural sector in France. France can be considered as a  
129 typical Western European country with intensive and diversified temperate agriculture: 68%  
130 of agricultural land as arable crops (wheat, barley, maize, rape and temporary grassland), 28%  
131 as permanent grassland, 4% as vineyard and fruit crops (2015 Annual farming statistics).  
132 Pursuant to national commitments on GHG mitigation, the French Environment and Energy  
133 Management Agency (ADEME), sought to clarify relative sector contributions to an  
134 economically efficient mitigation pathway. Accordingly, the French National Institute for  
135 Agricultural Research (INRA), was tasked with developing the analysis as a basis for  
136 subsequent incentive policies. Only measures related to agricultural management practices,  
137 with an expected abatement effect occurring at least partly on the farm, were considered. The  
138 proposed measures should not involve major changes in the agricultural production systems,  
139 their geographical distribution and their production level. They should be immediately  
140 implementable without additional research. The study was limited to the agricultural sector,  
141 thus excluding the forest sector.

## 142 143 **2. Methods**

### 144 145 2.1 Pre-selection of the proposed measures and sub-measures

146  
147 Compared to other MACC exercises (e.g. Moran et al 2011) that considered a broad range of  
148 technologies, some technically unproven, an initial decision in this study was to use an  
149 iterative procedure leading to detailed evaluation of a shorter list of immediately applicable  
150 measures. This process was informed by the availability of measure-specific expertise in the  
151 National Institute for Agronomic Research (INRA) to inform on key technical and economic  
152 variables defining measure applicability in different regions.

153  
154 An initial step screened around 100 mitigation measures, reorganised in 35 categories, which  
155 were found in the literature and used as a starting point for this study. Five criteria were used  
156 to shortlist 10 measures from this preliminary set:

157 The measure must be linked to an agricultural practice potentially chosen by the farmer, with  
158 at least part of the expected abatement located on the farm, requiring no major modification to  
159 the production system and with no reduction in yields exceeding -10%. Any measures  
160 targeting a sector upstream or downstream of the farm (e.g. human diets) or the agricultural  
161 sector, but with a mainly upstream or downstream effect (e.g. energy crops), or involving  
162 major changes in the production system (e.g. a change from conventional to organic farming)  
163 or having an excessively negative effect on production volumes (e.g. livestock reduction),  
164 were considered to be beyond the scope of the study.

165  
166 Measures whose abatement potential was judged to be low or uncertain were rejected. A  
167 potential was judged to be low either due to a modest unitary abatement and/or because the  
168 potential applicability of the measure, i.e. the surface areas or livestock numbers on which the  
169 application of the measure was technically possible, is limited in the French agricultural

170 context (e.g. measures concerning paddy fields, which represent 0.06% of the agricultural  
171 area in France). This preliminary assessment of the mitigation potential of each measure was  
172 based on results in the literature. For the 10 measures ultimately short-listed, this potential  
173 was calculated more precisely in the second step of the study.

174  
175 Measures were also screened in terms of readiness or availability of the technology required  
176 for implementation and of validated scientific knowledge demonstrating efficacy. For instance,  
177 measures still in the research stage, involving unproven technology, or for which applications  
178 are not yet available (e.g. genetic improvement of crops or livestock based on new criteria),  
179 were considered outside the scope of this study.

180  
181 Measures whose large scale feasibility was considered problematic (e.g. increasing soil pH  
182 over large areas), which implied known or suspected risks to health or to the environment,  
183 incompatible with current regulations (e.g. concerning the use of antibiotics in ruminants to  
184 reduce methane emissions) or with a low level of social acceptability (e.g. methods based on  
185 transgenesis) were rejected.

186  
187 Finally, synergistic or antagonistic effects with other major agri-environmental objectives (e.g.  
188 reducing the use of pesticides, improving water quality and preserving biodiversity) were also  
189 taken into account when making the final selection.

190  
191 Table 1 shows the 10 pre-selected measures comprising 26 sub-measures. Measures refer to  
192 categories of management practices (e.g. nitrogen fertilisation, tillage, livestock diets), while  
193 sub-measures refer to the specific technical levers enabling accurate calculations (e.g.  
194 fertilisation rate, application date, use of a nitrification inhibitor). Further calculations were  
195 thus performed at the sub-measure level. The 25 measures not selected and the reasons why  
196 are listed in Supplementary material.

## 197 198 2.2 Calculations

199  
200 Table 2 details the calculation of unitary abatements, unitary costs and the potential measure  
201 applicability and adoption scenarios. Table 3 lists main data sources for calculations. All  
202 abatement potentials were calculated in relation to the reference emissions for 2010. The  
203 common principles of calculations are described below.

### 204 205 2.2.1 Greenhouse gas emissions unitary abatement potential

206  
207 The unitary measure abatement potential (per hectare, per head of cattle) was calculated by  
208 reviewing all the sources of GHG emissions possibly affected by the measure concerned.

209 A distinction was made between direct (produced on the farm) and indirect emissions  
210 (occurring in the vicinity after physical transfer of molecules, for example nitrate leaching or  
211 ammonia volatilization) and induced emissions, which occur upstream or downstream of the  
212 farm, linked to changes in the purchase or sale of goods resulting from the measure (e.g. CO<sub>2</sub>  
213 emissions associated with the production of N fertilisers or avoided by the sale of renewable  
214 energy produced on the farm). Effects of management practices on radiative forcing through  
215 albedo were not considered.

216 As far as possible, calculations were performed using peer-reviewed references, including  
217 IPCC guidelines (IPCC, 2006) or modified based on references obtained in the French  
218 agricultural context. The unitary abatement was calculated for the three main gases (N<sub>2</sub>O, CH<sub>4</sub>  
219 and CO<sub>2</sub>), and then expressed in equivalent CO<sub>2</sub> (CO<sub>2</sub>e) using the 100-year global warming

220 potential values (GWPs) published in 2006 (298 for N<sub>2</sub>O, 25 for CH<sub>4</sub>, 1 for CO<sub>2</sub>) (IPCC,  
221 2006). Thus, unitary abatements were expressed in kg CO<sub>2</sub>e avoided per year and per unit, the  
222 unit depending on the sub-measure (hectare, animal, etc.) concerned. For comparison, a  
223 calculation based on current national inventory rules, using 1996 IPCC guidelines, was also  
224 performed (data not shown).

225

## 226 2.2.2 Unitary cost of the measure for the farmer

227

228 The unitary cost of each sub-measure was calculated including variations in direct costs  
229 (purchase of inputs, labour costs, etc.), investments if any, and changes in income associated  
230 with changes in production (yield losses if any, sale of additional products like wood or  
231 electricity). Costs were calculated using the prices of inputs and outputs in 2010 and results  
232 are expressed in 2010 euros (€). Delayed costs and benefits in the 2010-2030 scenarios were  
233 actualised using a 4% depreciation rate. This rate corresponds to the long run interest rate  
234 faced by the farmers during the 2000-2010 period. Scenarios did not incorporate any  
235 economic assumptions regarding market trends or expected changes in farm structure and  
236 operations resulting from market or technological trends. State subsidies were incorporated  
237 when they could not be separated from the used values (subsidised purchase of electricity  
238 produced by methanisation or tax exemptions for agricultural fuels for instance). Conversely  
239 "optional" subsidies like local subsidies (e.g. for methanisation) were not included. For  
240 comparison, a calculation excluding all subsidies was also performed.

241

## 242 2.2.3 Potential applicability of the measure and adoption scenario

243

244 The potential applicability of the measure was based on the number of farms, surface area or  
245 livestock numbers to which a measure was technically applicable in France. Technical rather  
246 than economic obstacles were considered. For example, agroforestry was only considered to  
247 be feasible on deep soils (>1 m) with high water holding capacity (>120 mm) so as to avoid  
248 excessive competition for water between trees and arable crops. Moreover, for practical  
249 reasons, agroforestry was considered to be feasible only on plots more than 4 hectares in size.  
250 Table 2 lists the criteria used to estimate the potential applicability of each sub-measure and  
251 the estimated value. French and international databases were used for calculations. An  
252 adoption scenario was then designed, starting from the reference situation in 2010 and ending  
253 in 2030. For many sub-measures, it was considered that the maximum potential applicability  
254 would be reached in 2030. For some, whose full adoption is expected to take longer (e.g.  
255 agroforestry, hedges, methanisation, flares), the percentage of the potential applicability  
256 reached in 2030 was estimated by experts in the field (table 2).

257

## 258 2.3 Marginal abatement cost curves (MACC)

259

260 A bottom-up MACC method was used for the inter-comparison of the 26 sub-measures. The  
261 two most widely used variables to compare abatement measures are the annual abatement  
262 potential and the cost per metric Mg of avoided CO<sub>2</sub>e. The annual abatement was calculated  
263 by multiplying the unitary abatement potential of each sub-measure by the potential  
264 applicability achieved in 2030. The cost per metric Mg of CO<sub>2</sub>e avoided was calculated as the  
265 ratio of unitary cost to unitary abatement.

266

## 267 3. Results

268

### 269 3.1 Abatement potential and cost of the 26 sub-measures

270

271 Figure 1 shows the cost to the farmer of the metric Mg of avoided CO<sub>2</sub>e (y axis) versus the  
272 annual GHG emissions abatement (x axis) for the 26 sub-measures ranked by increasing cost.  
273 Negative costs correspond to a gain for the farmer, generally linked to savings on inputs (so-  
274 called win-win measures), while positive costs represent a shortfall. Estimated costs range  
275 from – 515 € to + 530 € per metric Mg CO<sub>2</sub>e avoided. Annual abatements range from 0.08 Tg  
276 CO<sub>2</sub>e y<sup>-1</sup> (energy savings in greenhouses, a sub-measure which is already widely used) to 5.78  
277 Tg CO<sub>2</sub>e y<sup>-1</sup> (methanisation, a sub-measure which was only marginally applied in France in  
278 2010, but has high potential applicability). Assuming additivity, the cumulated abatement is  
279 32.3 Tg CO<sub>2</sub>e per year. Considering interactions between sub-measures (e.g. if N fertilisation  
280 rates of non-legume crops are reduced, then the abatement due to the substitution of these  
281 non-legume crops by legumes is reduced), the overall abatement becomes 28 Tg CO<sub>2</sub>e  
282 (calculation not shown). This slight reduction is due to the relative independence of most sub-  
283 measures covering a wide range of agricultural practices. This cumulated abatement cannot be  
284 directly compared to annual emissions from the agricultural sector in France as they are  
285 currently estimated using 1996 IPCC recommendations that differ from our calculation.  
286 Interestingly, the cumulated abatement of the 26 sub-measures calculated under current  
287 inventory rules was only 10 Tg CO<sub>2</sub>e y<sup>-1</sup>, which is about 10% of the emissions from the  
288 agricultural sector (105 Tg CO<sub>2</sub>e in 2010). This discrepancy is due to the fact that the  
289 expected abatement of several mitigation practices such as reduced tillage or modified animal  
290 diets cannot be accounted for by current inventory calculations, which are based on default  
291 values.

292

293 Figure 1 shows that the overall abatement potential can be divided into three approximately  
294 equal parts:

295

296 The first third of the expected overall abatement relates to sub-measures with a negative cost,  
297 i.e. resulting in a financial gain for the farmer. These sub-measures mainly involve technical  
298 adjustments which enable savings on inputs. This category includes sub-measures designed to  
299 save fossil fuel (adjustment of tractors and eco-driving 10C, insulation and improvement of  
300 heating systems used in greenhouses and livestock buildings 10B and 10A), adjustment of  
301 nitrogen fertilisation to realistic yield targets (1A), adjusting dates of fertiliser application to  
302 crop requirements (1C) and fertiliser placement (1E), taking nitrogen supplied by organic  
303 products into account more effectively (1B), adjustment of the amount of protein in animals  
304 diets (ruminants and monogastric animals, 8A and 8B) and sub-measures related to the  
305 management of pasture (extension of the grazing period 6A, increase in the proportion of  
306 legumes in pastures 2B, extension of the lifespan of temporary pasture 6B, making the most  
307 intensive grassland less intensive 6D). Nitrogen management in cropping systems (i.e.  
308 fertilisation of crops and pasture, including legumes in pasture) and livestock production (via  
309 feed) accounts for the largest share of the abatement potential linked with this first third.  
310 These are followed by grassland management and fossil fuel savings.

311

312 A further third of the expected overall abatement potential is linked to sub-measures with  
313 moderate cost (less than 25 euros per metric Mg of avoided CO<sub>2</sub>e). This category includes  
314 sub-measures which require specific investments (e.g. methanisation 9A) and/or associated  
315 with a slightly bigger modification of the cropping system (reduced tillage 3, agroforestry 5A,  
316 increase in legume crops 2A) which may result in modest reductions in yields (e.g. -2.1%  
317 with occasional tillage<sup>1</sup>), partly compensated for by a reduction in costs (fuels) or sales of

---

<sup>1</sup> This figure was derived from statistics provided by the French Ministry of Agriculture comparing yields under conventional and reduced tillage.

318 other products (electricity, wood).

319

320 The final third of the overall abatement potential is linked to sub-measures with higher cost  
321 (more than 25 euros per metric Mg of avoided CO<sub>2</sub>e). This category includes sub- measures  
322 requiring investment with no direct financial return (e.g. flares 9B), the purchase of particular  
323 inputs (e.g. nitrification inhibitor 1D, unsaturated fats or additives incorporated in the diet of  
324 ruminants 7A and 7B), dedicated labour time (e.g. cover crops 4A, hedges 5B) and/or  
325 involving bigger reductions in yields (e.g. grass buffer strips which reduce the cultivated  
326 surface area 4C), with little or no reduction in costs and no additional product for sale.

327

328 3.2 Effect of calculation assumptions on estimated abatements and costs

329

330 3.2.1 Effect of induced emissions on calculated abatements

331

332 Figure 2 shows the calculated abatement including all emissions (summing direct, indirect,  
333 induced) versus the calculated abatement including only direct plus indirect emissions. For  
334 clarity, the figure depicts potentials and costs at measure rather than sub-measure level.  
335 Several points were close to the bisector suggesting that, for these measures, considering  
336 induced emissions related to changes in the purchase or sale of products upstream or  
337 downstream of the farm as the result of the measure has little effect on the calculated  
338 abatement. This is especially the case for measures 3 (no-till), 4 (cover crops and grass buffer  
339 strips), 9 (methanisation) and 10 (reduce fossil fuel consumption). However, considering  
340 induced emissions considerably increases the potential calculated for measures related to the  
341 application of fertilisers (1) and the use of legumes (2), due to GHG emissions saved during  
342 the production of nitrogen fertilisers. This is also the case for agroforestry and hedges (5),  
343 because of the substitution effect of wood used as energy instead of fossil fuel. Conversely,  
344 when induced emissions are taken into account, this reduces the advantage of replacing  
345 carbohydrates by fats in cattle diet (7), resulting in an increase in upstream emissions for the  
346 production of raw materials.

347

348 3.2.2 Effect of subsidies on calculated costs

349

350 Table 4 shows the calculated costs including and excluding state subsidies for the three sub-  
351 measures mainly concerned. The subsidies considered here are only those that cannot be  
352 separated from current prices (such as subsidies when the electricity produced by  
353 methanisation is purchased and tax exemption for agricultural fuels). "Optional" subsidies,  
354 such as single payment entitlement (SPE), coupled aids and regional subsidies, were excluded  
355 from the cost calculations. For the majority of the sub-measures, subsidy inclusion does not or  
356 only slightly modifies the calculation of cost per metric Mg of avoided CO<sub>2</sub>e (data not shown).  
357 However, there is a bigger difference for the methanisation sub-measure, due to the subsidised  
358 purchase of the electricity produced. The difference is also notable in the sub-measures  
359 involving high direct energy consumption, given the implicit subsidy represented by the tax  
360 exemption for agricultural fuel.

361

## 362 4. Discussion

363

364 This study confirms that there is a significant abatement potential in the French agricultural  
365 sector. Assuming additivity, the overall abatement potential is estimated at 32.3 Tg CO<sub>2</sub>e per  
366 year in 2030 (28 Tg CO<sub>2</sub>e if interactions between sub-measures are considered). This  
367 abatement potential was obtained using a conservative approach, mainly based on readily

368 implementable technical measures for which there is a clear scientific consensus, either peer-  
369 reviewed or within INRA. The estimate was further reduced by rejecting measures involving  
370 major changes in production systems or which reduce yields (e.g. organic farming), still at a  
371 research stage (e.g. plant and animal breeding) or with low social acceptability (e.g.  
372 transgenesis). It is thus likely to be under-estimated. Additional measures which are still at the  
373 research stage are likely to become available in the near future. Moreover, for some of the  
374 selected measures whose full adoption is expected to take time, the percentage of the potential  
375 applicability reached in 2030 was estimated with caution (e.g. 7% for agroforestry). This  
376 suggests that an additional abatement potential exists if incentive policies encourage the  
377 adoption of these measures. Except for a few measures, the calculated abatement was not  
378 notably modified when emissions produced upstream or downstream of the farm were  
379 included. This shows that the selected measures can be implemented without any risk of  
380 emission swapping in other sectors or elsewhere in the world. As many barriers are known to  
381 hamper the adoption of climate smart agricultural practices (Long et al., 2016), a research  
382 effort is now required to identify the most cost-effective incentive policies.

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384 Interestingly, the total abatement was only 10 Tg CO<sub>2</sub>e per year when calculated under  
385 current inventory rules, which represents 10% of current emissions from the French  
386 agricultural sector. This underlines the need to upgrade these inventory rules, so that efforts to  
387 reduce emissions can be taken into account.

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389 One third of the total abatement potential was at negative cost thanks to input savings, and  
390 another third was at low cost (less than 25 euros per metric Mg of avoided CO<sub>2</sub>e). The results  
391 of the present study thus confirm that a large proportion of the abatement potential in  
392 agriculture can be obtained without reducing the profitability of agricultural activities - in fact,  
393 sometimes even increasing it - thanks to the reduction in GHG emissions and savings  
394 obtained by input savings enabled by technical adjustments (e.g. more efficient application of  
395 fertiliser). The reasons why these “win-win” measures are not readily implemented by farmers  
396 are discussed by Moran et al. (2013) and are the focus of ongoing research and policy in  
397 several countries.

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399 Among the 26 selected sub-measures, 12 are related to nitrogen management and represent 28%  
400 of the total potential abatement. Eight of these 12 sub-measures belong to the “win-win  
401 group”. The weighted average cost of N-related sub-measures is -54.5€ per metric Mg CO<sub>2</sub>e  
402 avoided whereas it is + 5.1€ per metric Mg CO<sub>2</sub>e avoided for all sub-measures. The  
403 abatement potential of these N related measures increases if emissions induced upstream are  
404 included, since the industrial production of nitrogen fertilisers is a highly energy consuming  
405 and GHG emitting process. Moreover, better management of the N cycle in agriculture is also  
406 expected to have positive effects on water and air quality. This identifies N management as a  
407 key lever for multi-agri-environmental purposes, not only reducing GHG emissions but also  
408 preserving water and air quality. The other key levers are linked to carbon storage in soils and  
409 biomass (30% of the total potential abatement), which also deserve other objectives (soil  
410 fertility, reduction of erosion risk), and energy savings and production on farms.

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412 The results of this study are difficult to compare with those of studies conducted in other  
413 countries because the criteria used to select the measures, the scope of abatement and cost  
414 calculation and the agricultural contexts are not the same (e.g. Eagle and Olander., 2012 for  
415 the USA; Moran et al., 2011 for the UK; O’Brien et al., 2014 for Ireland; Bellarby et al., 2013  
416 for Europe; Wang et al. 2014 for China; McKinsey & Company, 2009 for the world).  
417 However, certain similarities are clear:

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The assessment of the total abatement potential with respect to the reference emissions is comparable to that obtained in other countries in which a similar bottom-up approach was used. For instance, the abatement potentials represent 13% to 17% in the Irish study, 25% to 54% in the British study, and 58% in the global study conducted by McKinsey & Company. However, comparisons of this type should be interpreted with caution given the differences in scope, context, reference scenarios and in the methods used to calculate emissions, as well as the sensitivity of these results to the number and nature of the measures examined.

The range of unitary costs obtained in the French study (ranging from -€ 515 to € 530 per Mg CO<sub>2</sub>e) is comparable to that obtained in the Irish study. It is much narrower than that obtained in the British study, which included more "prospective" measures (e.g. use of ionophore antibiotics to reduce enteric CH<sub>4</sub> emissions). One of the features shared by the studies which assessed unitary abatement costs (McKinsey & Company, 2009; MacLeod et al., 2010; Moran et al., 2011; O'Brien et al., 2014) is that they provide a series of measures with negative or moderate costs. Several measures or sub-measures in this category can be found in many similar studies. This is true for application of nitrogen fertiliser, reduced tillage and grassland management. Their quantifications support the conclusions reached in the present study concerning the value of these levers. The proportion of the potential obtained with a negative cost (37% in this study) ranges from 20% to 74% in similar studies.

The ranking of the measures examined in the study by McKinsey & Company (2009) resembles the ranking made in the present study in several ways (e.g. relative ranking of measures with respect to fertiliser applications and feed additives), although the absolute values are not comparable due to differences in the scope of calculation. Some of the measures examined appear in other studies, but not all. This is true of measures targeting N management (UK), legumes (Ireland, UK, Europe), cover crops (USA, Europe), agroforestry (Europe), nitrogen content of livestock feed and fats/additives (UK) and methanisation (Ireland, Europe). Only the measure concerning fossil energy savings on the farm was only addressed in the French study. Conversely, some measures examined in other studies were not addressed in the French study. This is due to the different agricultural context (e.g. rice-growing), or the method of selecting measures which accepts a wider range of technologies (ionophore antibiotics or vaccines against methanogens, transgenesis). Similarly, levers that are promising in the long term but which are still in the research stage were not examined in our study (e.g. animal selection aimed at reducing methane emissions).

Finally, one of the major contributions of the present study is that it puts into perspective the sensitivity of the results to the emission and cost quantification method (abatement calculations based on current inventory rules or improved methods, inclusion or not of induced emissions, inclusion or not of state subsidies, etc.) when assessing the abatement potentials and costs. This aspect is largely absent from the other studies. It paves the way for the improvement of emissions inventories and underlines the importance of having a statistical framework capable of incorporating the environmental effects of farming practices.

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627 Table 1: List of the 10 measures and 26 sub-measures selected to reduce GHG emissions from  
 628 the agricultural sector in France  
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Measures and sub-measures		Targeted gas
<b>Reduce the application of mineral nitrogen fertilisers to reduce associated N<sub>2</sub>O emissions</b>		
①	<b>Reduce the use of synthetic mineral fertilisers:</b> 1A. Adjust fertiliser application rates to realistic yield targets - 1B. Make better use of organic fertiliser - 1C. Adjust application dates to crop requirements - 1D. Add a nitrification inhibitor - 1E. Incorporate fertiliser in the soil.	N <sub>2</sub> O
②	<b>Increase the use of legumes:</b> 2A. Introduce more grain legumes in arable crop rotations - 2B. Increase legumes in temporary grassland	N <sub>2</sub> O
<b>Store carbon in soil and biomass</b>		
③	<b>Develop no-till cropping systems:</b> Three technical options: continuous direct seeding, direct seeding with occasional tillage, i.e. 1 year out of 5, or continuous surface tillage	CO <sub>2</sub>
④	<b>Introduce more cover crops, vineyard/orchard cover cropping and grass buffer strips in cropping systems:</b> 4A. Extend the use of cover crops in arable cropping systems - 4B. Extend the use of cover crops in vineyards and orchards - 4C. Introduce grass buffer strips along waterways	CO <sub>2</sub> N <sub>2</sub> O
⑤	<b>Develop agroforestry and plant hedges:</b> 5A. Develop agroforestry with a low tree density - 5B. Plant hedges around the edges of fields	CO <sub>2</sub>
⑥	<b>Optimise grassland management:</b> 6A. Extend the grazing period - 6B. Increase the lifespan of temporary sown grassland - 6C. Make the most intensive permanent and temporary grassland less intensive - 6D. Make not very productive permanent grassland moderately more intensive	CO <sub>2</sub> N <sub>2</sub> O
<b>Modify animals' diets to reduce enteric CH<sub>4</sub> emissions and N<sub>2</sub>O emissions related to manure</b>		
⑦	<b>Replace carbohydrates with unsaturated fats and use an additive in the diet of ruminants:</b> 7A. Replace carbohydrates by unsaturated fats in the diet- 7B. Incorporate an additive (nitrate-based) in the diet	CH <sub>4</sub>
⑧	<b>Reduce the amount of protein in the diet of livestock:</b> 8A. Reduce the nitrogen content in the diet of dairy cows- 8B. Reduce the nitrogen content in the diet of pigs	N <sub>2</sub> O
<b>Recycle manure to produce energy and reduce fossil fuel consumption to reduce CH<sub>4</sub> and CO<sub>2</sub> emissions</b>		
⑨	<b>Extend methanisation and install flares:</b> 9A. Extend methanisation - 9B. Cover storage tanks and install flares	CH <sub>4</sub>
⑩	<b>Reduce consumption of fossil fuel by farm buildings and machinery:</b> 10A. To heat livestock buildings - 10B. To heat greenhouses- 10C. Consumed by agricultural machinery	CO <sub>2</sub>

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632 Table 2: Unitary abatement (UA, in kgCO<sub>2</sub>e/unit/year), unitary cost (UC, in €/unit/year) and  
633 maximum technical potential applicability (MTPA, in number of units) of sub-measures in  
634 2030. Unitary abatement includes only direct and indirect emissions, and excludes induced  
635 emissions (see text).  
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Sub-measures	UA(a)	UC(b)	MTPA(c)	Main modifications associated with the sub-measure and hypotheses for calculations of the unitary abatement, unitary cost and maximum technical potential applicability	Main sources	
<b>Reduce the application of mineral nitrogen fertilisers</b>	kgCO <sub>2</sub> e/ha/year	€/ha/year	millions of ha			
①	A. Adjust fertiliser application rates to realistic yield targets	222	-8.7	11.7	<b>Modification:</b> calculate the nitrogen balance using more realistic yield targets <b>UA:</b> -19.7 kgN/ha on average <b>UC:</b> €-18/ha (less N fertiliser); €+9.3/ha (cost of N management tools); no loss of production <b>MTPA:</b> fertilised arable crops (except sugar beet) and silage maize	<b>Fertiliser application practices:</b> 2006 "Cropping practices" survey <b>Surface area:</b> 2010 Annual farming statistics (SAA) <b>Prices, yields:</b> RICA 2010 database
	B. Make better use of organic fertiliser	156	-11.6	12.0	<b>Modification:</b> take organic N more effectively into account, reduce losses (volatilisation), increase volumes of recycled waste <b>UA:</b> -14.4 kgN/ha <b>UC:</b> €-13.1/ha (less N mineral fertiliser); €+1.5 (cost of incorporation); no loss of production <b>MTPA:</b> fertilised arable crops (except rice) and silage maize	
	C. Adjust application dates to crop requirements	231	-22.7	1.8	<b>Modification:</b> suppress the 1 <sup>st</sup> N application on winter crops <b>UA:</b> -15 kgN/ha; -30 kg CO <sub>2</sub> /ha (savings in fuel) <b>UC:</b> €-13.7/ha (less N mineral fertiliser); €-9/ha (saving in fuels); no loss of production <b>MTPA:</b> winter arable crops with high residual N	
	D. Add a nitrification inhibitor	262	15.8	2.3	<b>Modification:</b> use nitrification inhibitors (e.g. DMPP) <b>UA:</b> -10.2 kgN/ha; -3kg CO <sub>2</sub> /ha (savings in fuel due to fewer application dates) <b>UC:</b> €+31.2/ha (cost of inhibitor), €-9.3/ha (less N mineral fertiliser); €-6.1/ha (savings in fuels), no loss of production <b>MTPA:</b> arable crops (except sunflower, rice), return frequency of 1 year/5	
	E. Incorporate fertiliser in the soil	154	-9.1	3.7	<b>Modification:</b> incorporate fertilisers into the soil <b>UA:</b> -12.3 kgN/ha <b>UC:</b> €-11.2/ha (less N mineral fertiliser); €+2/ha (special equipment for seed drill); no loss of production <b>MTPA:</b> spring arable crops, using solid fertiliser at the time of sowing	
②	A. Introduce more grain legumes in arable crop	1044	19.4	0.88	<b>Modification:</b> include a grain legume instead of wheat (1/6), barley (2/3) and oilseed rape (1/6) <b>UA:</b> no N fertiliser needed on legume	<b>Current practices:</b> 2006 "Cropping Practices" survey

	rotations				crop, -33 kgN/ha on following crop <b>UC:</b> savings (N fertiliser, application operations), modification of the gross margin (legume and following crop) <b>MTPA:</b> except very stony soils (harvest problems) and soils with <80 mm water holding capacity (legumes are sensitive to water stress), return frequency of 1 year/6 to limit the risk of plant disease ( <i>Aphanomyces euteiches</i> )	<b>Fuel consumption values :</b> 2010 Centre – Ile-de-France region mutual aid scale <b>Surface area:</b> 2010 Annual farming statistics (SAA) <b>Soil characteristics:</b> INFOSOL INRA <b>Prices, yields, gross margins:</b> RICA 2010 database
	B. Increase legumes in temporary grasslands	171	-31.5	2.82	<b>Modification:</b> increase and maintain the proportion of legumes in temporary grassland <b>UA:</b> -29 kgN/ha on average <b>UC:</b> savings (fertiliser, application operations), yield not affected <b>MTPA:</b> all temporary grasslands with less than 40% legumes (no technical restrictions)	
<b>Store carbon in soil and biomass</b>		kgCO <sub>2</sub> e/ha/year	€/ha/year	millions of ha		
3	Switch to occasional tillage	389	3	10.1	<b>Modification:</b> switch from tillage or tillage every other year to direct seeding with tillage every 5 years <b>UA:</b> C storage (-100 kgC/ha/year); savings in fuel (-88 kgCO <sub>2</sub> /ha/year); higher N <sub>2</sub> O emissions (+56 kgCO <sub>2</sub> e/ha/year) <b>UC:</b> yield decreases 4 years out of 5 (-2.6%); more herbicides; savings in fuels and labour <b>MTPA:</b> arable surface areas (except potatoes, sugar beet, monocropped maize) and except poorly drained soils	<b>Current practices:</b> 2006 "Cropping Practices" survey <b>Surface area:</b> 2010 Annual farming statistics (SAA) <b>Soils characteristics:</b> Corine Land Cover data and INFOSOL INRA <b>Prices, yields:</b> RICA 2010 database
4	A. Extend the use of cover crops in arable cropping systems	252	41	4.3	<b>Modification:</b> cover crops composed of legumes (15% of surface areas), cover crops for long fallow periods and promoting previous crop volunteers <b>UA:</b> C storage (-240 kgC/ha/year), less N fertiliser (-11 kgN/ha) <b>UC:</b> fertiliser savings, more labour, no loss of production <b>MTPA:</b> only before spring crops, except soils with a clay content >60%, return frequency of 1 year/6 for legumes	<b>Current practices:</b> 2006 "Cropping Practices" survey <b>Surface area:</b> 2010 Annual farming statistics (SAA) <b>Soils characteristics:</b> Corine Land Cover data
	B. Extend the use of cover crops in vineyards and orchards	718	10	0.2	<b>Modification:</b> permanent cover crops (orchards, between every second row in some vineyards), and temporary cover crops (over the winter in some vineyards) <b>UA:</b> C storage (orchards: -490 kgC/ha/year, vineyards: -320) <b>UC:</b> more labor, no loss of production <b>MTPA:</b> all orchards (but 92% already have a cover crop); all vineyards except soils with a high percentage of coarse elements and dry climates	
	C. Introduce grass buffer strips along waterways	1200	633	0.25	<b>Modification:</b> plant grass buffer strips along water courses <b>UA:</b> C storage (-490 kgC/ha/year when replacing crop; 0 when replacing grassland); no N fertiliser <b>UC:</b> No inputs, no marketable product on	

					the green cover surface area <b>MTPA:</b> all edges of water courses	
5	A. Develop agroforestry with a low tree density	3717	49.6	5.9 but only 0.413 (=7%) reached in 2030	<b>Modification:</b> low density trees (30-50 trees/ha) within fields (annual crops) or on grassland <b>UA:</b> C storage (in soil, underground and above-ground biomass): -1.01 MgC/ha/year <b>UC:</b> investment in and maintenance of trees, production losses, but timber can be sold <b>MTPA:</b> all arable/grassland surface areas, with soil depth >1 m and water holding capacity >120 mm, fields > 4 ha	<b>Crop and grassland management:</b> 2006 "Cropping Practices" survey <b>Agroforestry management:</b> European Silvo-arable Agroforestry For Europe (SAFE) research project <b>Surface area:</b> 2010 Annual farming statistics (SAA) <b>Soils characteristics:</b> INFOSOL INRA <b>Prices, yields, gross margins:</b> RICA 2010 database
	B. Plant hedges around the edges of fields	702	75	12.1 but only 1.815 (=15%) reached in 2030	<b>Modification:</b> trees around the edges of fields in grassland and cultivated crops <b>UA:</b> C storage (soil and underground biomass): -0.15 MgC/ha/year in croplands (60 linear metres /ha) and 0.25 in grassland (100 lm/ha) <b>UC:</b> investment in and maintenance of trees, production losses, but wood can be sold <b>MTPA:</b> all arable and grassland surface areas, with soil depth >0.5 m, and fields > 4 ha	
6	A. Extend the grazing period	50	-26	4.0	<b>Modification:</b> extend the grazing season by 20 days <b>UA:</b> √ CH <sub>4</sub> and N <sub>2</sub> O from livestock, √ fuel consumption <b>UC:</b> √ in consumptions (manure, feed) <b>MTPA:</b> grasslands grazed by dairy cows or mixed dairy/beef herds; excluding farms where maize accounts for <10% of the main forage area	<b>Fertilisation levels and age of grassland:</b> 2006 "Cropping Practices" survey <b>Number of cattle and surface areas of grassland:</b> 2010 Annual farming statistics (SAA) <b>Feed ration typology:</b> Dairy cow diet observatory and French Livestock Institute <b>Prices, yields:</b> RICA 2010 database
	B. Increase the lifespan of temporary sown grassland	612	-112	2.35	<b>Modification:</b> increase the lifespan of sown grassland to 5 years <b>UA:</b> C storage (√ tillage): -0.14 MgC/ha/year, √ N <sub>2</sub> O (slower mineralisation), √ fuel consumption <b>UC:</b> √ in soil tillage and sowing <b>MTPA:</b> excluding temporary grasslands ≥ 5 years, and temporary grasslands in rotation with maize	
	C. Make the most intensive permanent and temporary grassland less intensive	52	-8	8.9	<b>Modification:</b> reduce applications of mineral fertiliser <b>UA:</b> √ fertiliser application (-5% to -25% depending on the current dose) <b>UC:</b> fertiliser savings (-€8/ha), no loss of production <b>MTPA:</b> grassland receiving mineral fertiliser	
	D. Make not very productive permanent grassland moderately more intensive	940	-4	0.5	<b>Modification:</b> ↗ 20% in livestock density (+0.24 LSU/ha) <b>UA:</b> C storage (↗ of primary production): -0.39 MgC/ha/year, ↗ CH <sub>4</sub> , N <sub>2</sub> O from livestock, ↗ fuel consumption <b>UC:</b> sale of hay (-€5.3/ha) <b>MTPA:</b> low productive grassland located close to other grazing land	
<b>Modify animals' diets</b>		kgCO <sub>2</sub> e/animal/y	€/animal/year	millions of animals		
7	A. Replace carbohydrates by	287	76.7	6.6 <sup>(1)</sup>	<b>Modification:</b> +3 to 3.5% of fatty acids in dry matter in the feed ration (4.5 to 5% in total)	<b>Numbers and categories of cattle:</b> 2010

	unsaturated fats in diets				<p><b>UA:</b> -14% CH<sub>4</sub> (for +3.5% fats)  <b>UC:</b> replace some of the carbohydrates with fats, no loss of production  <b>MTPA:</b> animals receiving &gt; 1 kg/day of feed concentrate during the period when they are indoors</p>	Annual farming statistics (SAA) <b>Feed ration typology:</b> Dairy cow diet observatory and French Livestock Institute
	B. Incorporate an additive (nitrate-based) in the diet	173	6.6	3.5 but only 2.8 (=80%) reached in 2030	<p><b>Modification:</b> the modified feed ration contains 1% nitrate  <b>UA:</b> -10% CH<sub>4</sub> (for 1% nitrate)  <b>UC:</b> purchase of nitrate and urea savings, no loss of production  <b>MTPA:</b> animals receiving a diet low in fermentable nitrogen when they are indoors</p>	
8	A. Reduce the nitrogen content in the diet of dairy cows	124	-11.6	1.96	<p><b>Modification:</b> √ crude protein in feed rations (target 14%)  <b>UA:</b> √ N<sub>2</sub>O emissions from manure (indoors, during storage, on grassland) and manure spreading  <b>UC:</b> modification of feed ration, √ milk production (-0 to 25 liters) and √ in protein content (-0.1 to -0.3 g/l)  <b>MTPA:</b> dairy cows with winter feed rations containing more than 14% crude protein</p>	<p><b>Animal numbers:</b> 2010 Annual farming statistics (SAA)  <b>Feed rations typology:</b> Dairy cow diet observatory and French Livestock Institute</p>
	B. Reduce the nitrogen content in the diet of pigs and sows	510	-49.2	0.95 <sup>(2)</sup>	<p><b>Modification:</b> synthetic amino acids and cereals in place of oil meals (soybean meal and rapeseed meal) and peas  <b>UA:</b> √ N<sub>2</sub>O emissions from manure (indoors, during storage, on grassland) and manure spreading  <b>UC:</b> modification of feed ration, no loss of production  <b>MTPA:</b> exclusion of boars and unproductive sows</p>	
<b>Recycle manure to produce energy, reduce fossil fuel consumption</b>		kgCO <sub>2</sub> e/unit/year	€/unit/year	Number of units		
9	A. Extend methanisation	473770 kgCO <sub>2</sub> e/farm/year	8283 €/farm/year	48800 farms but only 12200 (=25%) equipped in 2030	<p><b>Modification:</b> upstream outdoor storage limited to 3 weeks (duration √ by 88%), digestion in a reactor with energy production (50 kWe unit)  <b>UA:</b> √ CH<sub>4</sub>, √ N<sub>2</sub>O for solid manure only (anaerobic conditions)  <b>UC:</b> investment (€9000/kWe) and operating costs; sale of electricity  <b>MTPA:</b> farms with &gt; 140 LSU (i.e. 62% of total number of livestock)</p>	<p><b>Manure management practices:</b> Survey of livestock buildings  <b>Number of animals:</b> 2010 Annual farming statistics (SAA)  <b>Size of farm herd:</b> RICA 2010 database</p>
	B. Cover storage tanks and install flares	170000 kgCO <sub>2</sub> e/farm/year	10075 €/farm/year	40000 farms but only 20000 (=50%) equipped in 2030	<p><b>Modification:</b> capture and combustion of CH<sub>4</sub>, with no production of energy  <b>UA:</b> √ CH<sub>4</sub>  <b>UC:</b> investment (covering and flare) and operating costs (maintenance and monitoring)  <b>MTPA:</b> applied to liquid manure and only for livestock not concerned by methanisation</p>	
10	A. Reduce consumption of fossil fuel for heating livestock buildings	0.28 kgCO <sub>2</sub> e/animal produced	-0.081 €/animal produced	886 million animals produced per year but only	<p><b>Modification:</b> improve the heating and insulation system  <b>UA:</b> energy savings (from 15% to 50% depending on the technical options)  <b>UC:</b> investments and energy savings  <b>MTPA:</b> all meat poultry buildings</p>	<p><b>Current energy consumption:</b> Inter-trade technical centre for fruit and vegetables; Pig</p>

(meat poultry)			709 million (=80%) concerned in 2030		Institute; Technical institute for poultry farming <b>Number of animals:</b> 2010 Annual farming statistics (SAA) <b>Numbers and characteristics of tractors:</b> "Equipment" census (2005, Agreste)
A. Reduce consumption of fossil fuel for heating greenhouses	3.94 kgCO <sub>2</sub> e/m <sup>2</sup> /year	-0.57 €/m <sup>2</sup> /year	20.3 million m <sup>2</sup>	<b>Modification:</b> improve insulation and install hot water tanks <b>UA:</b> energy savings (from 5% to 22% depending on the technical options) <b>UC:</b> investments and energy savings <b>MTPA:</b> all greenhouses (25,4 million m <sup>2</sup> ) except those already equipped	
C. Reduce consumption of fossil fuel by agricultural machinery	2554 kgCO <sub>2</sub> e/tractor/year	-410 €/tractor/year	0.84 million tractors but only 0.64 million (=75%) concerned in 2030	<b>Modification:</b> eco-driving and adjustments after bench test <b>UA:</b> ∨ diesel consumption: bench test (-10%) and eco-driving (-20%) <b>UC:</b> costs (bench test, training for eco-driving) and energy savings <b>MTPA:</b> all tractors used (eco-driving), only recent tractors (1/3 of fleet) (test bench)	

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- (1) Millions of animal equivalent, pro rata basis depending on the length of the period during which their feed rations are modified  
(2) In the calculations, piglets and fattening pigs are assigned to sows (28.2 weaned piglets/year/sow)

640 Table 3: Main sources of data  
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Type of calculation	Data requirements	Sources and links
Abatement calculations	Crop management practices (fertiliser application, tillage, etc.)	Crop practices survey (Agreste - 2006)
	Animal feed rations	Technical institute references: for cattle (IDELE), for pork and pig (IFIP)
	Equations and emission factors used in the inventory	CITEPA 2012
	Emissions induced upstream/downstream	Carbone® database (ADEME) Dia'terre®-Ges'tim (Technical institutes)
Cost calculations	Crop and animal product prices	French Farm Accountancy Data Network (Agreste, RICA - 2010)
	Fertiliser prices	Eurostat
	Economic margins	French Farm Accountancy Data Network (Agreste, RICA - 2010)
	Cost of cultivation operations (ploughing, etc.)	CUMA (machinery cooperative) mutual aid scale 2010-2011
Potential applicability calculations	Crop surface areas	Annual statistics of agriculture (Agreste, SAA - 2010)
	Livestock numbers	French Farm Accountancy Data Network (Agreste, RICA - 2010)
	Yields	Geographic database for land use in France on a scale of 1/1 000 000 (BDGSF)
	Land characteristics and use	European land cover map (Corine Land Cover)

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644 Table 4: Calculated costs including or excluding state subsidies for three sub-measures  
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	Cost of the sub-measure (€ per metric Mg of CO <sub>2</sub> e avoided)	
	Including state subsidies	Excluding state subsidies
Develop methanisation (9A)	17	55
Switch to occasional tillage (3)	8	-13
Reduce consumption of fossil fuel by agricultural machinery (10C)	-164	-317

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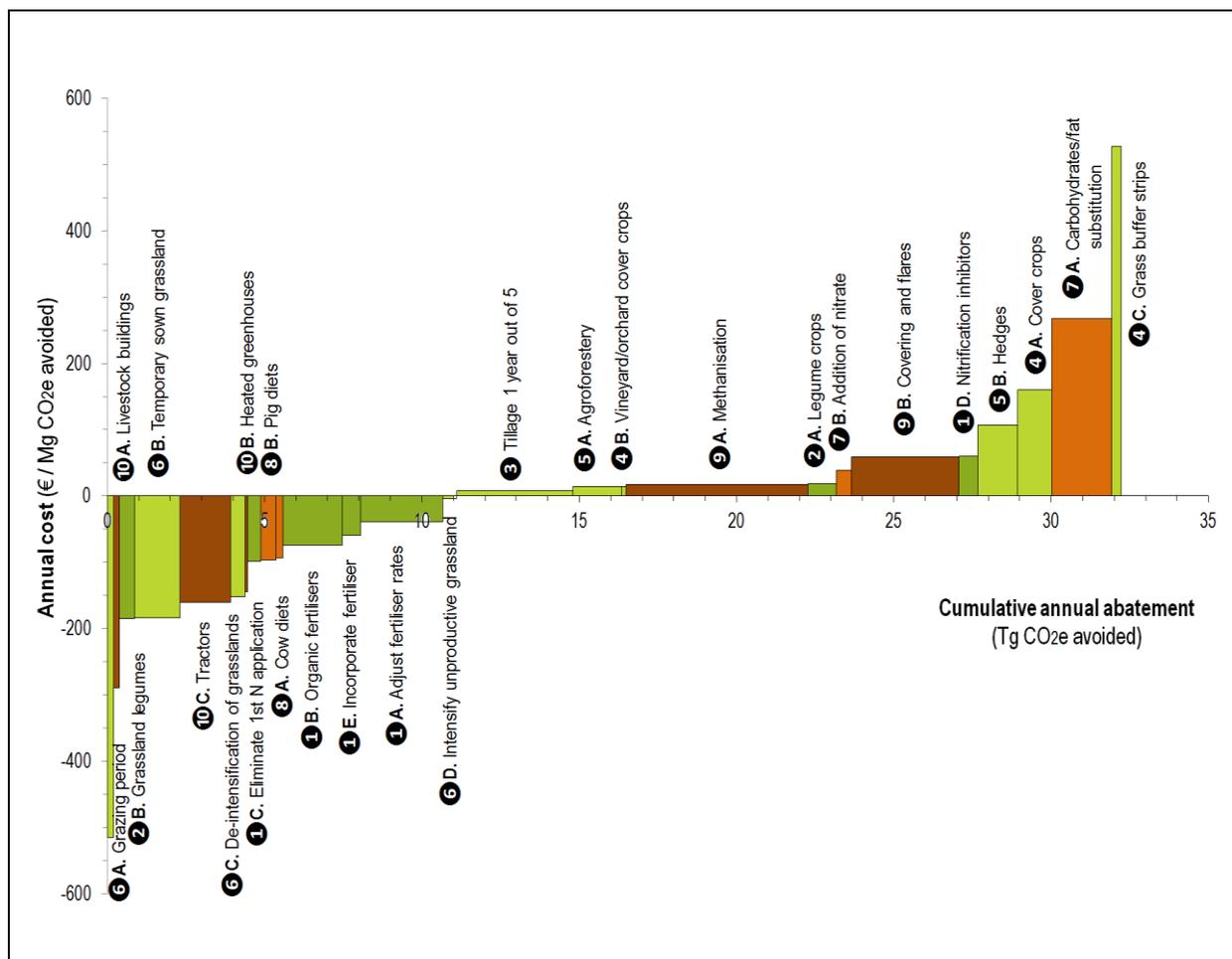


Figure 1: Cost (in € per metric Mg of CO<sub>2</sub>e avoided) and annual abatement potential in 2030 at the scale of mainland France (in Tg CO<sub>2</sub>e avoided per year) of the 26 sub-measures. The annual abatement was calculated not including induced emissions (see text). For measure 3 (develop no-till cropping systems) only the technical option “direct seeding with occasional tillage 1 year out of 5” is presented. Dark green: measures 1 and 2 (reduce the application of mineral nitrogen fertilisers); Light green: measures 3, 4, 5 and 6 (store carbon in soils and biomass); Orange: measures 7 and 8 (modify animal diets); Brown: measures 9 and 10 (recycle manure to produce energy and reduce fossil fuel consumption). See Table 1 for details.

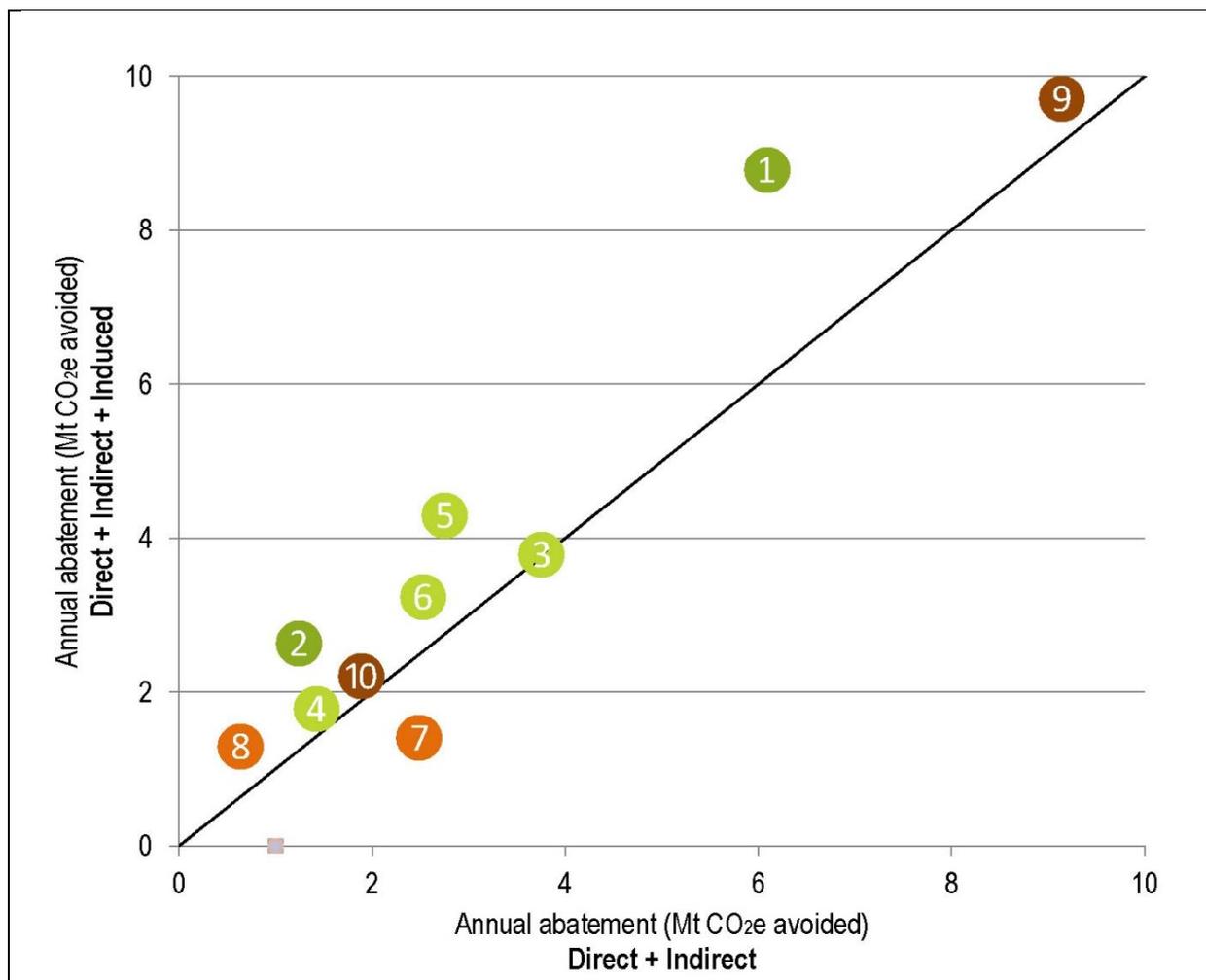


Figure 2: Total annual abatement per measure, including induced emissions, as a function of the abatement excluding induced emissions (in Tg CO<sub>2e</sub> per year, calculation for the year 2030). The number of each measure is given (for explanation, see Table 1).

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### Supplementary material: Measures not selected and why

Levers and measures	Reason it was not selected
<b>Modify the physicochemical conditions of soils to discourage CH<sub>4</sub> and N<sub>2</sub>O-producing reactions</b>	
Optimise the physical-chemical soil conditions to limit N <sub>2</sub> O emissions (for example, optimise pH by liming).	<i>The abatement potential is uncertain. N<sub>2</sub>O emissions depend on numerous factors including soil properties, climate, N fertilisation, tillage... (Stehfest and Bouwman, 2006). It is not easy to predict how changing physical-chemical properties would modify N<sub>2</sub>O flows and affect these flows on a national-wide scale, especially for soil pH (Van den Heuvel et al. 2011). In addition, the feasibility of modifying soil pH over large areas is subject to debate.</i>
Modify the microbial communities of soils by incorporating microorganisms that reduce N <sub>2</sub> O into N <sub>2</sub> (incorporation of Rhizobia strains living in symbiosis with legumes, for example).	<i>Still at the research stage. To date, mainly tested in laboratory conditions (Henault and Revellin, 2011) but rarely under field conditions (Akiyama et al., 2016).</i>
Promote aeration of rice-growing soil to reduce fermentation reactions and limit CH <sub>4</sub> emissions (reduce the depth of paddy	<i>Potential applicability is limited in France with only around 20,000 ha of paddy fields.</i>

fields, empty them several times a year, for example).	
<b>Reduce application of nitrogen fertiliser on crops to reduce N<sub>2</sub>O emissions</b>	
Genetically improve the nitrogen uptake and nitrogen use efficiency of crops to enable a reduction in nitrogen fertiliser application.	<i>Not applicable in the short term. Long term breeding programs are required before this measure will be efficient.</i>
<b>Reduce CO<sub>2</sub> losses to the atmosphere by reducing flows from biomass and soils</b>	
Limit export of organic matter from cultivated fields to limit carbon losses from the soil (e.g. do not burn crop residues in the field).	<i>The abatement potential is low since burning crop residues is rare in France where most crop residues are already returned to the soil.</i>
Avoid cultivating wet zones to limit the release of CO <sub>2</sub> stored in organic matter.	<i>Potential applicability is limited in France because there are few cultivated zones that could be returned to wet zones.</i>
<b>Increase CO<sub>2</sub> inputs through increased biomass production, thereby increasing flows from the atmosphere towards biomass and soils</b>	
Increase the production of biomass by optimising production factors in order to increase the return of carbon to the soil.	<i>The abatement potential is low since French agriculture is already very intensive. Increasing production implies increasing fertiliser application or irrigation, which results in emissions of other GHGs. In addition this measure could conflict with other public policies.</i>
Adjust the selection of species of cultivated crop to increase the return of carbon to the soil (crops with a higher return level, deep-rooted or permanent plants, for example).	<i>Not applicable in the short term. Long term breeding programs are required before this measure will be efficient. Moreover, this measure may have a significant impact on the types of production and its abatement potential is uncertain, particularly for deep-rooted plants.</i>
Restore degraded soil to increase organic matter production and store carbon in soil (acidified, eroded, saline soils).	<i>Potential applicability is limited in France.</i>
Spread "inert" carbon (biochars, plant charcoal) on cultivated land to store carbon.	<i>Still at the research stage. The unitary abatement potential is uncertain and little is currently known about the impact on soils and agricultural production (Atkinson et al., 2010; Gurwick et al., 2013)</i>
<b>Increase livestock productivity to reduce per head CH<sub>4</sub> and N<sub>2</sub>O emissions</b>	
Select livestock on the basis of growth rate, milk production or prolificacy traits.	<i>Animal breeding for productivity is a long term process that is already underway.</i>
Select cattle on the basis of residual feed consumption criteria (efficiency of nutrient use) or directly on the basis of CH <sub>4</sub> emissions.	<i>Breeding animals to match these new criteria is a long term project (Eckard et al., 2010). Moreover, the heritability of enteric CH<sub>4</sub> emission and its genetic correlation with other traits were not known when the present study started (Basarab et al., 2013).</i>
Improve herd management and health to increase livestock productivity.	<i>The abatement potential is low given that this approach to herd management is already implemented in France.</i>
Use products that increase per head production (meat or milk).	<i>The use of bovine somatotropin, the only additive proven to be effective on milk production, is banned in the European Union.</i>
Develop mixed breeds or industrial cross-breeding in cattle to reduce per head GHG emissions.	<i>This measure would significantly modify livestock farming systems and its abatement potential per kg of milk or meat is uncertain.</i>
<b>Alter rumen function to reduce enteric CH<sub>4</sub> emissions</b>	
Regulate populations of microorganisms promoting the production of methane in the rumen using antibiotics.	<i>The use of antibiotics for non-curative purposes is banned in the European Union.</i>

Act on the rumen microorganisms by regulating bacteria, protozoa and methanogen populations using biotechnologies: anti-methanogen vaccines, inoculation of specific yeast or bacteria strains, chemical additives (chloride or bromide derivatives) or natural additives (essential oils, plant extracts).	<i>Biotechnologies capable of modifying the microbial ecosystem of the rumen are still at the research stage (Martin et al., 2010; Hristov et al., 2013; Jeyanathan et al., 2014). When the present study began, such additives had not demonstrated a systematic and long-term in vivo effect and some have a low level of social acceptability (Eckard et al., 2010).</i>
<b>Modify feed to reduce CH<sub>4</sub> and N<sub>2</sub>O emissions</b>	
Modify the nutritional characteristics of forage, favoring non-methanogenic substances (increase the tannin or saponin content of forage for instance).	<i>Still at the research stage (Beauchemin et al., 2008). In vivo effects have not yet been demonstrated for saponin (Guyader et al., 2015). Tannins are efficient for decreasing methane (Rira et al., 2015) but have a negative effect on intake (Hristov et al., 2013)</i>
Increase the percentage of feed concentrate in the diet.	<i>The sustainability of ruminant livestock systems based on the use of imported concentrate-rich diets is questionable. Reductions of direct emissions are likely to be at least partially offset by higher induced emissions upstream (Doreau et al., 2011).</i>
<b>Optimise manure management</b>	
Reduce the amount of livestock manure stored in order to reduce CH <sub>4</sub> emissions due to manure fermentation	<i>Storage is necessary to wait for the most suitable spreading time and to optimize utilization of nutrients (Burton and Turner, 2003). Consequently, application of this measure is limited and the expected effect is partially covered by the sub-measures 6A (extending the grazing period) and 9A (developing methanisation)</i>
Optimise the type of manure produced to obtain a CH <sub>4</sub> /N <sub>2</sub> O balance minimising the global warming potential per unit of manure (favour solid manure rather than slurry, composting, etc.).	<i>The global abatement potential is uncertain, because CH<sub>4</sub> and N<sub>2</sub>O are produced during the whole management process and emissions are controlled by many factors (Chadwick et al., 2011).</i>
Optimise manure management and storage to reduce N <sub>2</sub> O and CH <sub>4</sub> emissions	<i>Measure initially selected but subsequently abandoned due to the technical difficulties involved in examining it</i>
<b>Produce energy from biomass or livestock manure</b>	
Produce dihydrogen from livestock manure using an anaerobic process and convert it into energy.	<i>Still at the research stage. Technical obstacles need to be overcome, particularly the chronic instability of the processes</i>
Produce energy on the farm by biomass combustion	<i>Dedicated energy crops are outside the scope of this study (see introduction). Energy production from biomass produced on farm without replacing food crops is partially included in sub-measure 5B (conversion of hedge wood into energy)</i>
<b>Reduce fossil energy consumption on farm</b>	
Use solar energy to naturally dry agricultural products and reduce energy requirements for post-harvesting drying (e.g. reduce the moisture level of maize at the time of harvest).	<i>A significant proportion of the expected abatement is located outside the farm (lower energy consumption by collect organisations)</i>

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