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# 1 **The cost of emissions mitigation by legume crops in French**

## 2 **agriculture**

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11

## 12 **Abstract**

13

14 This paper considers the cost of greenhouse gas mitigation potential of legume crops in  
15 French arable systems. We construct marginal abatement cost curves to represent this  
16 mitigation or abatement potential for each department of France and provide a spatial  
17 representation of its extent. Despite some uncertainty, the measure appears to offer significant  
18 low cost mitigation potential. We estimate that the measure could abate half of the emissions  
19 reduction sought by a national plan for the reduction of chemical fertilizers emissions by  
20 2020. This would be achieved at a loss of farmlands profit of 1,2%. Considering the  
21 geographical heterogeneity of cost, we suggest that a policy implementing carbon pricing in  
22 agriculture would be more efficient than a uniform regulatory requirement for including the  
23 crop in arable systems.

24

25 Key words: Agriculture, greenhouse gas mitigation, legumes, cost-effectiveness

26

27

## 28 **1 Introduction**

29

30 Agriculture accounts for a significant proportion of total greenhouse gas (GHG) emissions  
31 both in France and at the European level. In 2011, European Union agriculture accounted for  
32 461 million tCO<sub>2</sub>eq, while in France the amount was 92,5 million tCO<sub>2</sub>eq (respectively 10,8  
33 and 20,6% of European and French GHG emissions including land use, land use change and  
34 forestry according to UNFCCC<sup>1</sup> National Inventory Report, 2013). A recent European  
35 Commission communication (European Commission, 2014) on the policy framework for  
36 climate and energy indicated that emissions from sectors outside the EU Emission Trading  
37 Scheme (EU-ETS) would need to be cut by 30% below the 2005 level by 2030. At the same  
38 time, within the framework of the 'energy-climate' package France has committed to reduce  
39 emissions of its sectors not covered by the EU-ETS by 14% by 2020 compared to 2005  
40 emissions levels (European Union, 2009).

41

42 Given these ambitions, there is increasing scrutiny of the mitigation measures and specifically  
43 their cost relative to other option available within agriculture and in other sectors. This paper  
44 considers the abatement of emissions from crop fertilization, which represents a major source  
45 of emissions from French agriculture (a fifth of French agricultural emissions<sup>2</sup>). This  
46 comprises emissions of nitrous oxide mainly emitted during the process of denitrification of  
47 nitrogenous fertilizers spread on arable land. The paper assesses the overall abatement

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<sup>1</sup> United Nations Framework Convention on Climate Change.

<sup>2</sup> Calculated by dividing the 20,29 MtCO<sub>2</sub>eq emissions from crops (see appendix A) by the 94,3 MtCO<sub>2</sub>eq French agricultural emissions (CITEPA, 2012).

48 potential of a key measure, the introduction of leguminous crops, and the associated costs and  
49 co-benefits in farm systems.

50

51 Legumes (fabaceae), commonly known in France as alfalfa, pea, or bean family, have the  
52 ability to naturally fix atmospheric nitrogen and can reduce N<sub>2</sub>O emissions compared with  
53 conventional crops (maize, wheat, barley, oilseed, rape). This function is conferred by  
54 rhizobium bacteria that live in symbiosis at the level of their roots in little organs called  
55 nodules. As a consequence, they need far less fertilizer thanks to the fixing effect allowing  
56 nitrogen to stay in the ground for up to two years after planting. This contributes additional  
57 amounts of nitrogen to subsequent crop in rotations. Studying alternative crop emissions,  
58 Jeuffroy et al. (2013) demonstrated that legume crops emit around five to seven times less  
59 GHG per unit area compared with other crops. Measuring N<sub>2</sub>O fluxes from different crops  
60 they show that peas emitted 69 kgN<sub>2</sub>O/ha; far less than winter wheat (368 kgN<sub>2</sub>O/ha) and  
61 rape emissions (534,3 kgN<sub>2</sub>O/ha). Moreover, compared to the emissions from cattle meat  
62 production, human consumption of peas instead of meat leads to 85 to 210 times less N<sub>2</sub>O  
63 emissions for the same content of protein ingested<sup>3</sup>. Despite this mitigation benefit, N-fixing  
64 crops have low agronomic performance (see appendix A) and consequently their introduction  
65 in arable systems will, in most regions, incur a penalty in terms of farm revenue.

66

67 Recent research (Pellerin et al. 2013) has suggested the cost of GHG mitigation via grain  
68 legumes at around 19 euros/tCO<sub>2</sub>eq. This paper scrutinises this assessment by proposing three

---

<sup>3</sup> 20-37 gN<sub>2</sub>O/kg protein for meat and 0,17-0,23 gN<sub>2</sub>O/kg protein for peas. The amount of emissions for meat is obtained using the N<sub>2</sub>O content from feed fertilization and manure management included in cattle meat from Dollé *et al.* (2011) of 3,026 kgCO<sub>2</sub>eq and 1,615 kgCO<sub>2</sub>eq per kg of meat. The amount of emissions for pea is obtained using the yield of 25-34 q/ha from Agreste data..The protein content of meat (27,6g/100g) and peas (8,8 g/100g) required for the calculation are from Ciquel (2012).

69 improvements: (1) determining the spatial variation of cost across French Departments; (2)  
70 studying how cost varies according to reduction targets; and (3) analyzing the sensitivity of  
71 the abatement cost with respect to agricultural seed prices and farmers' ability to exploit low  
72 abatement cost.

73

74 Here, abatement cost assessment is linked to the substitution of other arable crops by legume  
75 crops in farmlands simulating two consecutive years, so as to integrate the fixing effect of the  
76 preceding period. This methodology allows the derivation of a marginal abatement cost curve  
77 for each French metropolitan geographical area<sup>4</sup>. The results are then subject to a sensitivity  
78 analysis to examine growers' responses to low cost abatement, crops prices and agricultural  
79 input prices.

80

81 The paper is structured as follows. The next section presents the context of N-fixing crops  
82 cultivation in France and in Europe and section 3 analyses abatement cost assessment in the  
83 scientific literature. Section 4 describes the methodology. Section 5 analyses the results and  
84 compares them with the previous INRA (National Institute of Agronomic Research) study  
85 (Pellerin *et al.*, 2013). Finally, a discussion considers the policy relevance of carbon pricing to  
86 promote N-fixing crops.

87

## 88 **2 Context**

89

---

<sup>4</sup> Each geographical area corresponds to a department. In the administrative divisions of France, the department (French: *département*) is one of the three levels of government below the national level. It is situated between the region and the *commune*.

90 Despite their beneficial properties, the area planted to legumes in France has been on a steady  
91 downward trend. For fodder legumes the fall started in the 1960's from a high of 17% of the  
92 French arable land. The area then decreased steadily, reaching 2% in 2010 (Duc et al. 2010).  
93 For grain legumes, the fall began later at the end of the 1980's after years of political effort to  
94 develop them through the common agricultural policy (CAP) (Cavaillès, 2009).

95  
96 This decline is due to several factors. First an increasingly meat-based diet incorporating less  
97 vegetable proteins led to lower consumption of legumes by humans. The General Commission  
98 for Sustainable Development reports that in France between 1920 and 1985 human seed  
99 legume consumption fell from 7,3 kg/person/year to 1,4 kg/person/year (Cavaillès, 2009).

100 This trend coincided with a change in livestock feeding regimes, with legume-based rations  
101 being increasingly replaced by maize silage, grass plants and imported soybean meal. The loss  
102 of agricultural nitrogen due to this switch in farmlands was compensated by chemical  
103 fertilizers, which had become increasingly price-competitive since the 1960's.  
104 Simultaneously, trade agreements on the abolition of customs tariffs between Europe and the  
105 United States favored American soybean imports. Finally, a lack of agronomic research  
106 dedicated to legumes compared with common crops, led to a relative decrease of their  
107 agronomic performance (Cavaillès, 2009).

108  
109 In France, as in the rest of the European Union (EU) these factors have led to a strong  
110 dependency on soya imported from America to feed livestock. In 2009, soya was the largest  
111 food commodity imported into the EU (12,5 million tons) ahead of palm oil and bananas  
112 (FAO<sup>5</sup>). These imports come mainly from South America (49% from Brazil and 31% from  
113 Argentina (European Commission, 2011)), and at a significant cost : the average annual trade

---

<sup>5</sup> <http://faostat.fao.org/>

114 balance, calculated over the period 2004-2008, represented a loss equivalent to 1 billion euros  
115 (Cavaillès, 2009) for France and up to 10,9 billion euros for the EU. It follows that increasing  
116 legume areas in French agriculture can both mitigate GHG emissions and limit dependency on  
117 feed imports. This is all the more so given the trend of increasing chemical fertilizer prices. In  
118 2010, the price of fertilizers and soil conditioners spread on farmland in France were some  
119 65% higher than 1990; this increase being largely related to higher global energy prices. Thus,  
120 the increasing scarcity of fossil fuels provides another reason to explore the potential  
121 development of legume crops.

122

### 123 **3 Cost-effectiveness analysis in the literature**

124

125 For cost-effectiveness analysis Vermont and De Cara (2010) identify three broad approaches  
126 for the derivation of marginal abatement cost curves (MACCs), the device typically used to  
127 evaluate pollution abatement costs and benefits. These are: i) a bottom-up or engineering  
128 approach; ii) an economic approach consisting of modeling the economic optimization of a set  
129 of (in this case) farm operations; iii) a partial or general equilibrium approach that extends and  
130 relaxes some of the assumptions about wider price effects induced by mitigation activity.

131

132 The engineering approach focuses on the potential emission reduction of individual measures  
133 and observes their cumulated abatement and associated costs. The required data to appraise  
134 abatement costs are ideally collected from measures applied on test farms, thereby reducing  
135 some uncertainty the estimated cost and mitigation potential for each mitigation measure. It is  
136 normally the case that more measures are assessed using the engineering approach relative to  
137 the economic approach (MacLeod et al. 2010, Moran et al. 2010, Pellerin et al. 2013).

138



139 The economic approach consists of modeling the economic optimization of a set of farm  
140 operations located within a given geographical scale. The objective function is typically to  
141 maximize profit of these farms under given constraints such as available arable land or even  
142 lay fallow land as imposed by agricultural policies. The introduction of a carbon tax as a new  
143 constraint, allows the model to reconfigure farm activities to accommodate the necessary  
144 GHG emissions reductions. The resulting loss in profit (opportunity cost) and GHG reduction  
145 provide the relevant abatement cost information.

146

147 Equilibrium models relax some of the cost assumptions made in the economic approach and  
148 include a description of the demand for agricultural products thereby allowing a price  
149 feedback into the cost of mitigation (Vermont and De Cara, 2014). Their level of spatial  
150 disaggregation is generally lower than that of bottom-up models and their geographic scope  
151 and coverage are generally wider. This approach has been used to assess abatement cost at the  
152 level of the USA (Schneider and McCarl, 2006; Schneider et al., 2007; McCarl and  
153 Schneider, 2001).

154

155 A noteworthy difference between the approaches is the frequent observation of negative cost  
156 options in the engineer approach for some options (Moran et al., 2010; MacKinsey &  
157 Company, 2009). These are obviated in any optimization approach and are in any case  
158 questioned by some authors. Kesicki and Ekins (2012) for example suggest that they more  
159 likely imply a failure to assess some hidden costs (diffusion of the information, administration  
160 barriers) than any real opportunity to reduce emissions while increasing farm gross margins.  
161 Another observation is that each mitigation measure in the engineering approach is associated  
162 with a constant marginal cost – creating a stepwise marginal abatement curve (each step  
163 corresponding to an option). This observation suggests that the economic potential per ton

164 CO<sub>2</sub> equivalent mitigation is the same for each specific option irrespective of spatial scale or  
165 in terms of the overall volume of emission reduction, which would seem unlikely. Indeed, due  
166 to regional variability in soils, farm systems, climate and yields, abatement cost would also  
167 vary for any individual mitigation measure.

168  
169 Results from studies employing the economic approach are depicted by continuous increasing  
170 abatement cost curves, with no negative cost. An advantage of these studies is optimization of  
171 fewer mitigation measures over a large number of farm types. For example De Cara and Jayet  
172 (2011) modeled around 1300 EU farms optimizing animal feed, a reduction in livestock  
173 numbers, a reduction of fertilization and the conversion of croplands to grasslands or forests.

174  
175 Legumes have been specifically assessed in a UK study constructing a national MACC for  
176 agricultural GHG emissions (Moran *et al.*, 2010). The marginal abatement cost obtained for  
177 legume crops appears constant and very high (14280 £/tCO<sub>2</sub>eq equivalent to 17000  
178 euros/tCO<sub>2</sub>eq). This is in stark contrast to Pellerin *et al.* (2013) estimate of only 19 euros/t  
179 CO<sub>2</sub>eq. To explore some of the reasons for this disparity we adopt a predominantly  
180 engineering approach combined with elements of an economic approach to explore the role of  
181 farm systems decision-making around the adoption of legumes as a specific measure that can  
182 influence farm profitability.

183

## 184 **4 Method**

185

### 186 4.1 Defining emissions and gross margin

187 The analysis assesses the abatement potential in 96 French metropolitan geographical areas,  
188 each considered as a single farm decision unit. The analysis is confined to the within farm

189 gate effects and does not account for the upstream or downstream impacts; e.g. associated  
 190 with lower fertilizer production, or the emission mitigation benefit related to enteric  
 191 fermentation of cattle consuming legumes (McCaughey et al., 1999). In each geographical  
 192 area, farmland emissions and profits are calculated and decomposed for each crop (Common  
 193 Wheat, Durum Wheat, Barley, Maize, Sunflower, Rapeseed, Pea, Horse bean and Alfalfa).

194 We followed the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC,  
 195 2006) to estimate N<sub>2</sub>O emissions per hectare. Using mineral nitrogen spreading rates and  
 196 organic spreading rates from the Agricultural Practices survey (Agreste, 2010) we calculate  
 197 the following kinds of emission sources:

- 198 - direct emissions, happening directly on the field,
- 199 - indirect emissions, covering emissions from atmospheric redeposition and leaching  
 200 and runoff,
- 201 - emissions from crop residues.

202 The formula that determines each crop gross margin in each geographical area is summarized  
 203 as follows (Ecophyto R&D, 2009) :

$$GM_{k,i} = (price_{k,i} \times yield_{k,i}) - (exp_{phyto,k,i} + exp_{ferti,k,i} + exp_{seed,k,i})$$

204

205 Where GM<sub>k,i</sub> is the gross margin calculation for each crop i in each geographical area k (in  
 206 euro per ha). Price<sub>k,i</sub> is the crop price in euros per ton and yield<sub>k,i</sub> is expressed in tons per  
 207 hectare. The expenses in phytosanitary products (exp<sub>phyto,k,i</sub>), in fertilizers spread (exp<sub>ferti,k,i</sub>)  
 208 and in seed (exp<sub>seed,k,i</sub>) are all measured in euros per hectare.

#### 209 4.2. Baseline

210 Appendix A shows the results for the main crops cultivated in France and gives the baseline  
 211 for overall farmland gross margin (6,4 billion euros) and for emissions (20,4 MtCO<sub>2</sub>eq).  
 212 When comparing these emissions with those of the national inventory report, we observe that  
 213 the amount represents less than half of the category ‘Agricultural Soils’ (46,7 MtCO<sub>2</sub>eq  
 214 (CITEPA, 2012)). This category represents all N<sub>2</sub>O emissions linked to soil fertilization both  
 215 from cropland and grassland soils. Hence the baseline emissions assessed here is quite  
 216 coherent since we only focus here on emissions from croplands which represent less than half  
 217 of the French Utilized Land Area<sup>6</sup>.

#### 218 4.3. Introduction of legumes onto croplands

219 Legume crops have low emissions per hectare and a low gross margin compared with other  
 220 crops. Consequently, in most geographical areas, as the overall utilized land area remains  
 221 constant, increasing the share of in N-fixing crops induces a reduction of both profit and  
 222 emissions.

223 Additional legume crop areas are introduced in each geographical area by 10% increments to  
 224 the initial legumes area. The loss of profit (dCost) divided by the reduction of emission  
 225 (dEmissions) linked to these additional areas represents the marginal abatement cost. The  
 226 marginal cost and marginal emissions also integrate the preceding fixing effect, which induces  
 227 higher gross margin and lower emission for following year crops that have been preceded by  
 228 legumes.

$$\text{Marginal Abatement Cost} = \frac{d\text{Cost}}{d\text{Emissions}}$$

---

<sup>6</sup> According to Agreste, the Utilized Land Area represents 28 million hectare in France. In appendix A, we observe that cropland area covers less than half of this area: 13,6 million hectares.

229 Legume substitution continues until a marginal abatement cost of 125 euros/tCO<sub>2</sub>eq has been  
230 exceeded per geographical area. This upper abatement cost threshold has been arbitrarily  
231 chosen, considering the relative abatement cost in other sectors (Vermont and De Cara,  
232 2014)<sup>7</sup>.

233 In seeking the lowest abatement cost in terms of foregone gross margin per unit emissions, we  
234 assume that legume crops displace conventional (non N fixing) crops according to a schedule  
235 of progressively increasing gross margin. Thus areas yielding lowest gross margin are  
236 converted first. But to avoid complete displacement of conventional crops, a cap is placed on  
237 the extent of this displacement. The logic here is that it is difficult to foresee that farmers  
238 would be entirely motivated by an abatement cost goal to cultivate legumes to the exclusion  
239 of other crops. In reality most farmers would seek to minimize risk by maintaining a level of  
240 diversity on their land, which often means that they maintain less profitable crops. For  
241 instance, on livestock farms, some less profitable crops are used for feed. In other cases a lack  
242 of training and information can also retard the adoption of new practices such as legumes. We  
243 consider scenarios in which the limit, termed the variable limit, is assumed to take alternative  
244 values of 10%, 30%, 90% and 100%. When the variable limit is 100%, farmers can  
245 potentially replace all the crop area, meaning that they are looking for a complete  
246 minimization of abatement cost and are strongly sensitive to economic signals for mitigation.  
247 On the other hand, a 10% limit means that farmers cannot replace more than 10% of the least  
248 profitable crops area. Moreover, we account for the fact that the variable limit is the same for  
249 every crop in every geographical area. Allowing for agronomic differences, different national  
250 abatement cost curves are therefore presented for the different variable limits: from the 10%

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<sup>7</sup> Vermont and De Cara, 2014 assesses for instance a marginal abatement cost curve for European farms until a maximum level of 100 euros/tCO<sub>2</sub>eq

251 scenario corresponding to a low exploitation of minimal abatement cost to a complete use of  
252 low abatement cost in the 100% scenario.

253 As legume crops are introduced onto farmland the cumulated cost corresponds to the sum  
254 of dCost and the cumulated abatement corresponds to the sum of dEmissions generated at  
255 each additional area introduction. These cumulated cost and abatement are obtained both at  
256 the regional and national levels. The average mitigation cost is the ratio between cumulated  
257 cost and cumulated abatement. Figure 1 illustrates a sample geographical area in which  
258 legumes area is increased with a 50% limit. Agricultural land is allocated with only 5 crops,  
259 each characterized by a specific emissions rate per hectare and gross margin. Assume the rank  
260 of crops considering their ratios of gross margin per emissions is : crop i, crop j, crop l and  
261 crop m. Thus, the additional area of legumes first replaces crops i. Once crop i has lost 50% of  
262 its area, legumes replace crop j, and so on until the introduction reaches crop m. At this stage,  
263 the 125 euros/tCO<sub>2</sub>eq is achieved, which consequently stops further legume introduction.

264 [Figure 1]

265 The marginal abatement cost of successive areas increments is depicted in figure 2. Each  
266 point of the curve corresponds to an additional increase in legume area. For a given crop, the  
267 marginal abatement cost is the same whatever the replaced area, which explains the different  
268 steps of the curve. The values comprising the overall abatement cost curve is derived from the  
269 integral of the marginal abatement cost curve.

270 [Figure 2]

## 271 **5 Results**

### 272 5.1 Abatement potentials and cost

273

274 At the national level and assuming the variable limit of 100%, the maximum technical  
275 abatement of 2,5 million tCO<sub>2</sub>eq/year is possible for an overall cost of 118 million euros/year  
276 (see figure 3. c). This corresponds to an increase of 1,6 Mha of legumes and an average  
277 abatement cost of 43 euros/tCO<sub>2</sub>eq.

278

279 The overall cost depends on the volume of emissions reduction. Since displaced crops in each  
280 geographical area are ordered by their ratio of gross margin per emission, the lower the  
281 abatement targets the lower the overall cost. For example, if the target of emission reduction  
282 is reduced by 30%, to 1,7 MtCO<sub>2</sub>eq, the average abatement cost is reduced by 80% to 14  
283 euros/tCO<sub>2</sub>eq. If the target is lower than 1,4 MtCO<sub>2</sub>eq, we find a negative abatement cost,  
284 implying that legumes are actually now more profitable than the crop that is displaced .

285

286 Reducing the variable limit also reduces the overall abatement potential while increasing the  
287 abatement cost. Fixing the limit to either 10% or 90% induces a reduction in the maximum  
288 abatement potential of 84% and 8% respectively. We thus observe that results are highly  
289 sensitive to this variable. But even if the variable is low, we still observe opportunities to  
290 reduce emissions while increasing farm gross margins (see figure 3).

291

292 Pellerin et al. (2013) suggests that legume introduction could provide an overall abatement  
293 potential of 0,9 MtCO<sub>2</sub>eq, at a cost of 17 million euros. This implies an average mitigation  
294 cost of 19 euros/tCO<sub>2</sub>eq. That study did not consider how cost varies with area and hence the  
295 potential for negative costs. By illustrating those results (the blue curve in Figures 3b and 3c)  
296 alongside those derived in this study, it is possible to see that defining a variable limit of 50%,  
297 which is the average scenario, and the most realistic, for the same amount of emission abated,

298 we obtain the same overall cost and the same average abatement cost (reached for a marginal  
299 abatement cost of 80 euros/tCO<sub>2</sub>eq).

300

301 [Figure 3 a]

302 [Figure 3 b]

303 [Figure 3 c]

304

## 305 5.2 Heterogeneity of abatement cost between French geographical areas

306

307 The spatial allocation of the abatement potential between different geographical areas can be  
308 represented for the same marginal abatement cost. Figure 4 shows the departmental shares for  
309 the same marginal carbon reduction cost threshold (80 euros/tCO<sub>2</sub>eq) and a 50% limit to  
310 achieve the same reduction estimated by Pellerin et al. (2013). The results show considerable  
311 geographical variability, with some accounting for a small amount of the 0,9 MtCO<sub>2</sub>eq  
312 national abatement. These geographical areas are mainly located in the south and eastern parts  
313 of France, and represent each less than 1% of these overall reduced emissions. Departments  
314 with the highest potential are located in the north-west, where the majority of the geographical  
315 areas represent each more than 1% of the national abatement. Note that two regions, Orne and  
316 Manche, can each contribute more than 10% of the national abatement.

317

318 An alternative representation of the cost heterogeneity is presented in figure 5 for three  
319 geographical areas: Orne, Haute-Vienne and Côtes d'Armor. Introducing legumes in Orne is  
320 more profitable than in Haute-Vienne or in Côtes d'Armor. In the latter two regions, even for  
321 low levels of mitigation the marginal abatement cost is high (respectively 80 euros/tCO<sub>2</sub>eq  
322 and 110 euros/tCO<sub>2</sub>eq). This cost heterogeneity demonstrates the challenge of setting a



323 uniform nationwide target. If, for example the objective of reducing 50 000 tCO<sub>2</sub>eq GHG  
324 emissions were assigned for the three previously mentioned geographical areas, the overall  
325 cost would be high relative to the case of one region (Orne), mitigating 130 000 tCO<sub>2</sub>eq on its  
326 own. As a result, this simulation demonstrates the advantages of policy instruments that  
327 account for the cost heterogeneity between regions.

328 [Figure 4]

329 [Figure 5]

### 330 5.3 Sensitivity analysis

331  
332 Figure 6 shows the impact on the abatement cost of price variations of conventional crops.  
333 When seed prices of alternative crops increase, the opportunity cost of legume introduction  
334 rises. On the contrary, when seed prices decrease, the difference of gross margin between  
335 legumes and conventional crops decreases as well and makes their introduction less costly.  
336 We represent the abatement curves for the follow price increases: -20%, +20% and +50%. For  
337 a price decrease of -20%, negative abatement costs appear until an abatement level of 6  
338 MtCO<sub>2</sub>eq. For a price increase of 20%, the opportunity of decreasing emissions while  
339 increasing profit disappears completely. The abatement cost becomes considerably high when  
340 the increase is 50%. Consequently, we observe a strong sensitivity of abatement cost to the  
341 price of conventional crops.

342  
343 Abatement costs are also highly sensitive to agricultural input prices (fertilizers, seeds and  
344 phytosanitary products) (figure 7). A rise of 20% of input prices compared to baseline values  
345 determined in the Ecophyto R&D (2009) favors legume introduction by lowering the  
346 abatement cost. A higher increase of 50% for a marginal abatement cost of 30 euros/tCO<sub>2</sub>eq  
347 increases the abatement from 0,8 to 2 million tons CO<sub>2</sub> equivalent. On markets, input prices

348 are not so volatile. Although they rose sharply in 2008-2009, this spike was exceptional  
349 relative to recent trends showing more stable increases. The prospect of rising fossil fuel  
350 prices, which are inputs to phytosanitary products manufacturing, suggests that the  
351 opportunity cost of legumes may be lower in the future.

352 [Figure 6 a]

353 [Figure 6 b]

354 [Figure 6 c]

355 [Figure 7 a]

356 [Figure 7 b]

357 [Figure 7 c]

358

## 359 **6. Discussion**

360

361 A problematic observation in the analysis is the presence of negative abatement costs, which  
362 raises questions about their veracity. Specifically, it is unclear why farmers would not  
363 automatically adopt such profitable measures (and provide associated mitigation) unless it is  
364 the case that there are other unaccounted for costs driving decision-making, which are not  
365 captured in this analysis. These hidden costs can be attributed to a variety of barriers within  
366 and beyond the farm. Some barriers are intrinsic to individual behaviors and imply internal  
367 factors (cognition and habit) and social factors (norms and roles) (Moran *et al.* 2013).  
368 Moreover, farmers may be exhibiting risk aversion behavior in response to legume yield  
369 variation. In this study, the average legume gross margin is relatively high in some regions,  
370 making the crop in rotations more profitable than some of the conventional crops. However,  
371 the annual yield of legume disguises significant annual variation that is not represented here.  
372 Consequently some farmers, actually grow crops with a lower gross margin to be sure that the

373 yield of the crop will be high enough and to avoid any risk of significant loss associated to  
374 legumes. This risk aversion is also linked to the volatility of other crop prices, which has a  
375 strong impact on abatement cost as shown in figure 5. Furthermore, as noted by Gouldson  
376 (2008), some factors are external to the farm. These include a necessity to adapt the  
377 organization of agricultural cooperatives to collect the output of legumes. For instance,  
378 legumes need adapted silos that are not currently established in all regions in France. The role  
379 of cooperatives is also important in the diffusion of information, training and advice in the  
380 agricultural sector (Meynard *et al.*, 2013).

381  
382 Beyond the apparent paradox of non adoption of negative cost measures, a broader challenge  
383 relates to the available policy options available for agricultural mitigation. The CAP reform  
384 framework for the 2014-2020 period elevates emissions mitigation as a significant challenges  
385 for agriculture (European Commission, 2014). But ongoing debate about the reform is notable  
386 for the limited scope of explicit GHG mitigation objectives that are nevertheless being  
387 analyzed at national level in several countries (e.g. UK, Ireland, and Netherlands). In France,  
388 the Court of Auditors has indicated that climate policy should not only focus on the energy  
389 and industry sectors through the EU-ETS, but also on sectors with small and diffuse  
390 emissions sources, in particular agriculture (Cour des Comptes, 2014). A similar situation can  
391 be observed in the UK, where abatement cost analysis has helped to define an economic  
392 abatement potential that is initially being targeted through voluntary agreement with the  
393 agricultural sector (AHDB, 2011). The point now at issue is the relevant policy instrument to  
394 motivate these emissions reductions at least cost.

395  
396 The fact that abatement costs vary strongly from one geographical area to another suggests  
397 that these instruments should rely more on market-based approaches, rather than a regulatory

398 approach aimed at increasing legumes area directly. Such approaches (e.g. a tax or forms of  
399 emissions permits) offer the flexibility of response, thereby increasing the likelihood of  
400 realizing the abatement potential identified by marginal abatement cost curves. Specifically,  
401 when a carbon price is implemented in a specific sector, agents should reduce their emission  
402 until the marginal abatement cost reaches the carbon price (de Perthuis et al., 2010).

403

404 In the case of domestic projects, a carbon price can compensate the costs due to the  
405 introduction of additional legume area. In this way, agents will continue to reduce their  
406 emissions as long as marginal abatement costs are lower than the benefit of the carbon  
407 annuity. Thus, legumes areas rise while minimizing overall abatement cost; in contrast to a  
408 blanket regulatory requirement that specifies the area to be planted.

409

410 For illustration, we compare the two approaches for the same target for increasing legumes  
411 (doubling the current area at national level). This target is chosen since it corresponds to an  
412 area that should be cultivated in France to reduce dependence on soya imports (Cavaillès,  
413 2009). In the carbon pricing approach, a doubling of legumes at national level happens at a  
414 carbon price of 80 euros/tCO<sub>2</sub>eq. In the uniform regulatory approach, each geographical area  
415 is required to double its legumes area. On the face of it, the latter approach appears logical if  
416 we consider that each region increases area in proportion of the initial area. Yet, we observe  
417 in table 1 that for the same target, the overall abatement cost is far lower under a carbon price  
418 (18 million euros) than under a uniform target (127 million euros).

419

420 An experimental initiative with offset payments for legume cultivation is currently being  
421 piloted on a voluntary basis by some regional cooperatives (InVivo, 2011). Farmers willing to  
422 increase the share of legumes on their land receive a carbon annuity, determined by the level

423 of carbon price on the EU ETS<sup>8</sup>. However, few cooperatives have been part of this initiative.  
424 Indeed, the carbon price being relatively low at 5 euros/tCO<sub>2</sub>eq (CDC Climat, 2014) the offer  
425 is not attractive for farmers. An advantage of the MACC analysis presented here is to assess  
426 the impact on abatement if this initiative were to become more widespread, subsequently to  
427 higher carbon price level.

428 [Table 1]

## 429 **7. Conclusion**

430  
431 Combining both economic and engineering approaches to the development of abatement cost  
432 curves, this study offers a national assessment of the cost-effectiveness of GHG mitigation  
433 using legumes in arable systems. This intermediate MACC approach allows for the possibility  
434 of negative abatement costs that are typically excluded in economic approaches to MACC  
435 construction. It also reveals more granularity in cost information that is usually disguised in  
436 the average cost assumptions made in engineering approaches. This is particularly  
437 advantageous for illustrating uncertainties linked to agricultural price variation (agricultural  
438 input and seed prices volatility) and some hypotheses about the reaction of farmers to  
439 economic signals. Finally the approach is useful to display regional variability in costs and  
440 hence to illuminate the efficiency of policy alternatives for the introduction of the measure.

441  
442 In a realistic scenario, legumes could abate a maximum 7% of chemical fertilizer emissions at  
443 a cost of 77 million euros corresponding to a loss of 1,2% of overall profit in France. Win-win  
444 abatement could be 3% of chemical fertilizer emissions. Hence, although showing that this

---

<sup>8</sup> This project is led under the framework of the Joint Implementation  
([http://unfccc.int/kyoto\\_protocol/mechanisms/joint\\_implementation/items/1674.php](http://unfccc.int/kyoto_protocol/mechanisms/joint_implementation/items/1674.php)). An assessment report of  
the project is drawn up at the moment and should be delivered in the period of January-February 2015.

445 mitigation option could offer low abatement cost, N-fixing crop would need to be combined  
446 with other measures to tackle the 14% emissions reduction target of diffuse emissions sectors  
447 by 2020 (European Union, 2009). To increase adoption the suggested option of carbon pricing  
448 would appear to be more economically efficient than a policy focusing on increasing areas in  
449 each geographical area directly.

450

451 An interesting addition to this work would be to investigate the upstream and downstream  
452 impact of legume on greenhouse gases and their consequences on abatement cost. The  
453 production of chemical fertilizers is responsible for significant CO<sub>2</sub> emissions in industries.  
454 Hence, the associated decrease of emissions due to chemical fertilizers substitution should  
455 decrease abatement cost. Further, the displacement of imported soybean by fodder legumes  
456 such as alfalfa would have a positive impact on enteric fermentation, responsible for methane  
457 emissions in livestock feeding regimes (Martin et al., 2006). It would also via indirect land  
458 use change (De Cara, 2013) impact land use emissions of countries where soybean is  
459 currently produced. Accordingly, studying impacts beyond the farm gate would be a useful  
460 extension.

461

462 Finally, further research should seek a more disaggregated level with several farms inside the  
463 geographical area scope. Currently, the decision unit is at the level of the department.  
464 Providing a more disaggregated level of analysis below the focus would be worthwhile  
465 especially by distinguishing different groups of farms below this level. In the different  
466 scenarios concerning the impact of the variable limit, we assume that all farmers have the  
467 same response toward economic signals, but reality shows that farmer behaviours are diverse  
468 (Dury, 2011; Glenk et al., 2014). In this regard characterizing groups of farmers with specific  
469 variable limits would be of interest.

470

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472

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476 for its financial support.

477

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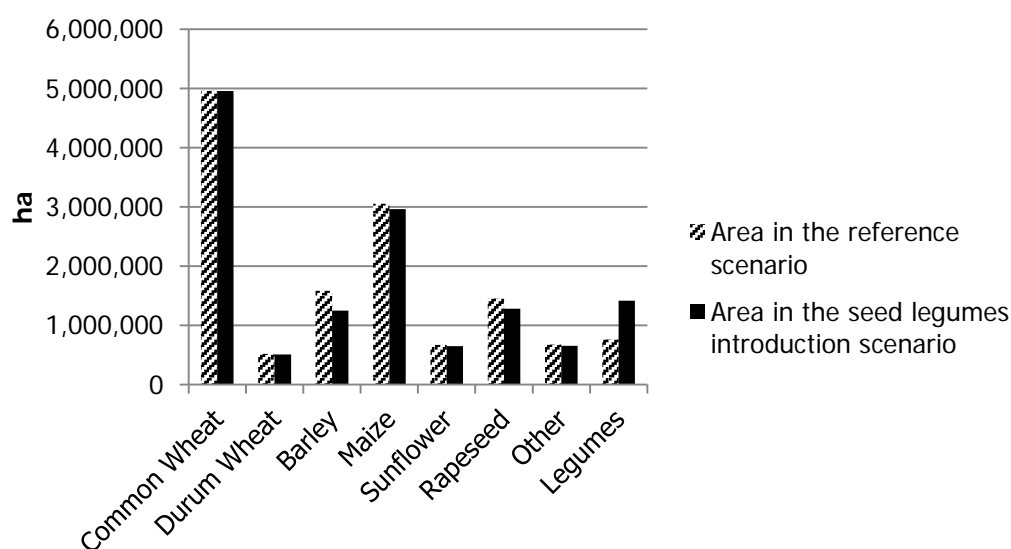
635

636 **Appendix A – Area, emissions and gross margin for the main crops in France at the**  
 637 **national level in the baseline situation**

	Area	Average Emissions	Overall Emissions	Average GM	Profit
	ha	kgCO <sub>2</sub> eq/ha	MtCO <sub>2</sub> eq	euros/ha	Meuros
Common Wheat	4 961 435	1 323	6,56	546	2 709
Durum Wheat	519 852	1 512	0,79	377	196
Barley	1 581 969	1 222	1,93	365	577
Maize	3 051 075	2 230	6,81	588	1 794
Sunflower	671 075	1 356	0,91	293	197
Rapeseed	1 452 744	1 528	2,22	360	523
Other	672 539	1 552	1,04	422	284
Legumes (pea, alfalfa, horse bean)	763 049	35,4	0,03	122	93
<b>All Crops</b>	<b>13 673 738</b>	<b>-</b>	<b>20,29</b>	<b>-</b>	<b>6 372,90</b>

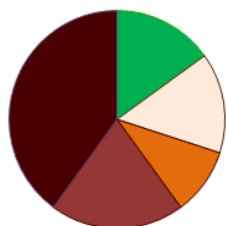
638

639 **Appendix B – Impact on legume introduction on other cereals area (for a carbon price**  
 640 **of 80 euros/tCO<sub>2</sub>eq with a limit of 50%)**



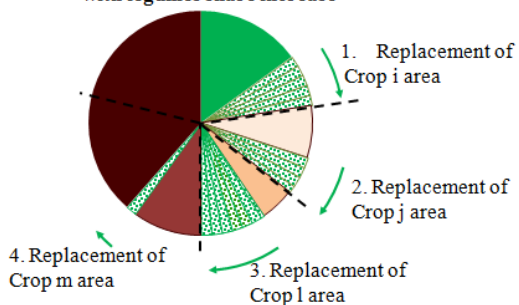
641 **Figures**

Reference for Cropland Allocation



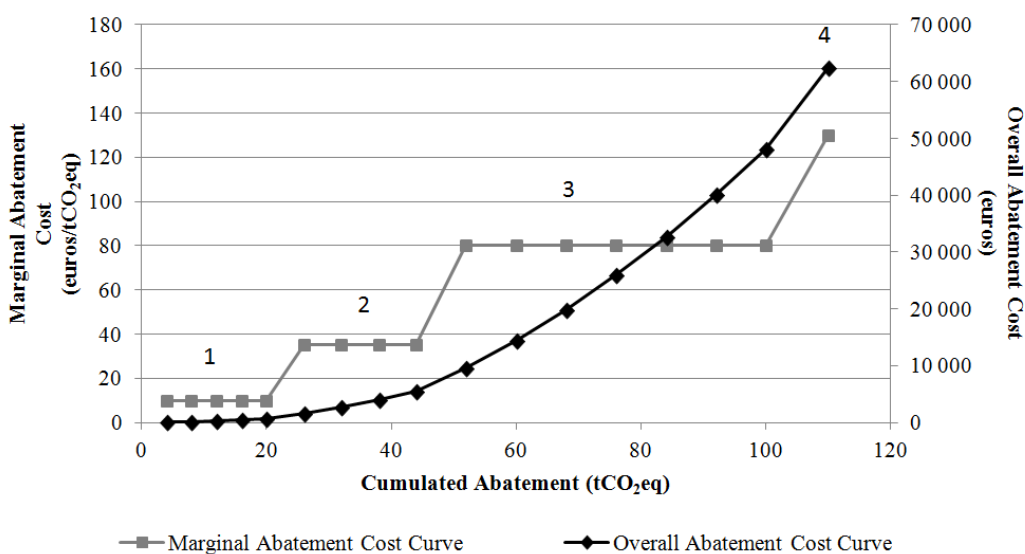
- Legumes
- Crop i
- Crop j
- Crop l
- Crop m
- Legumes Areas Taken over other crops
- - 50% Limit of replacement

Crop land allocation with legumes share increase



642

643 Figure 1: Illustration of legume area increase in farmlands at the departmental scale



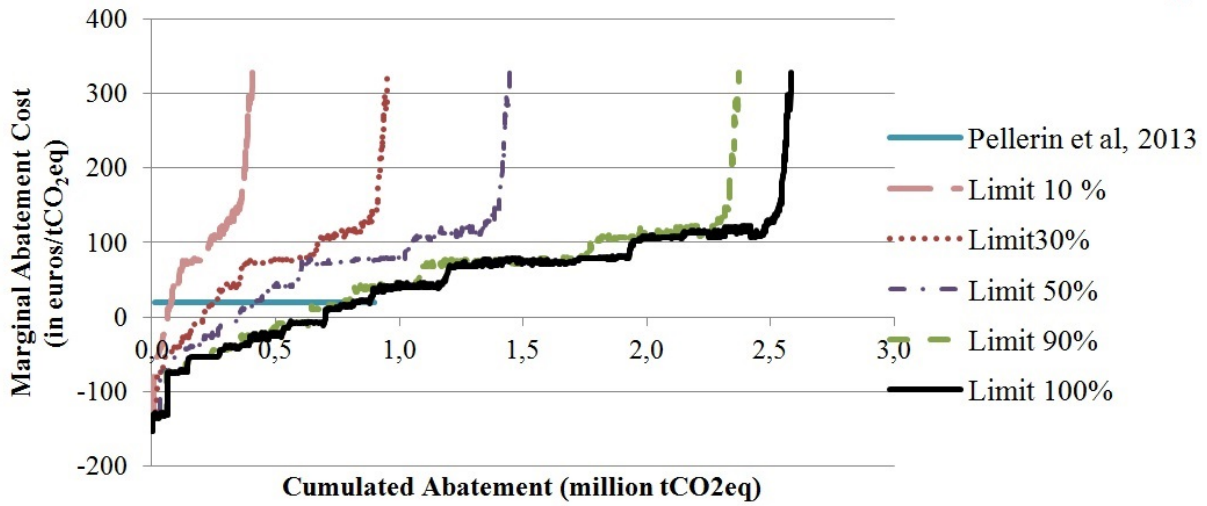
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645 Figure 2: Illustrative marginal and overall abatement cost curves linked to increasing legume

646 area on farmland



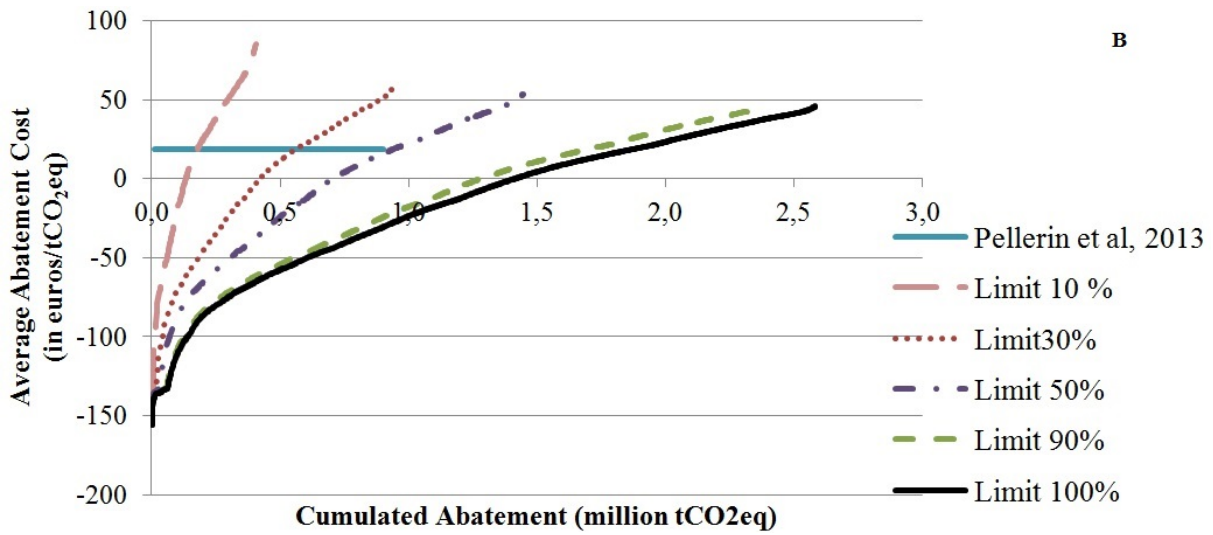
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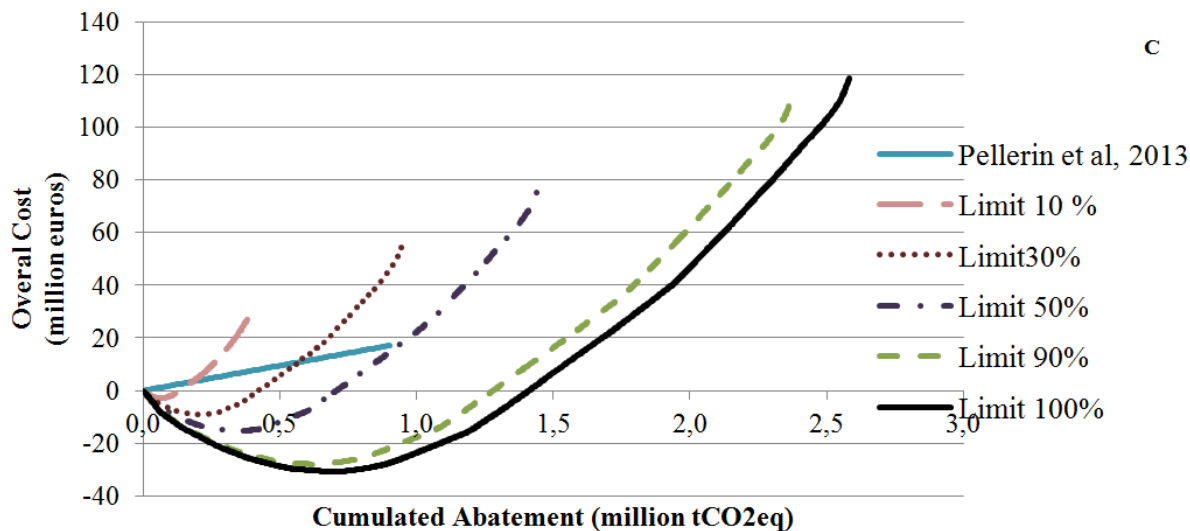
648 Figure 3 a

B



649

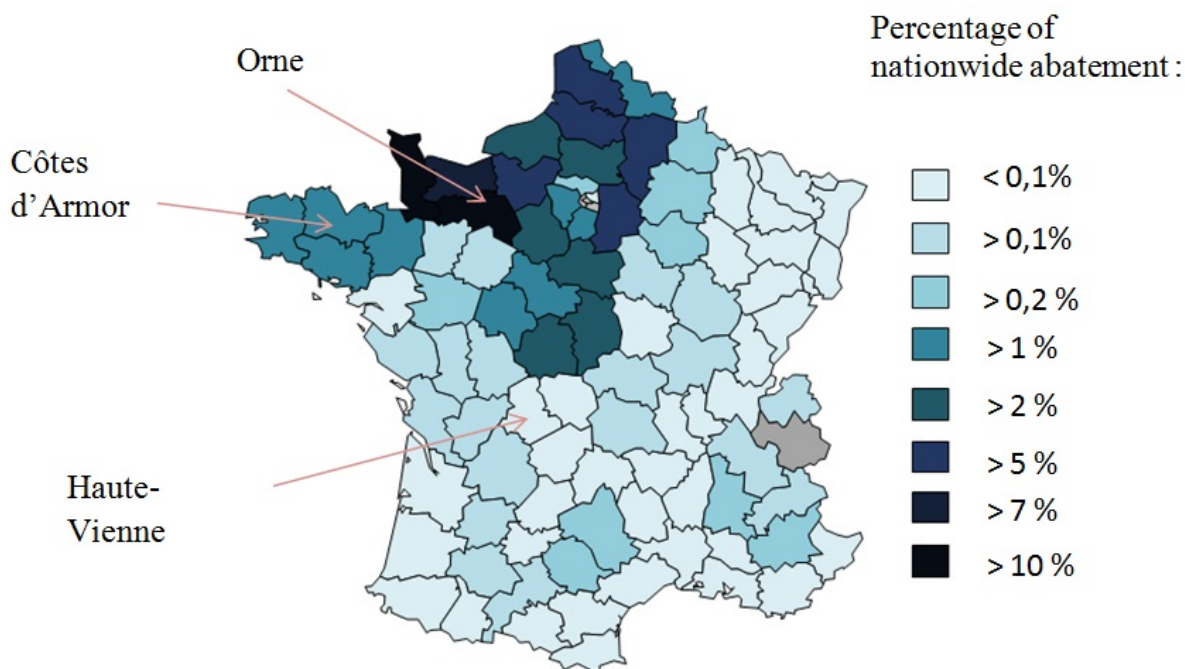
650 Figure 3 b



651

652 Figure 3 c

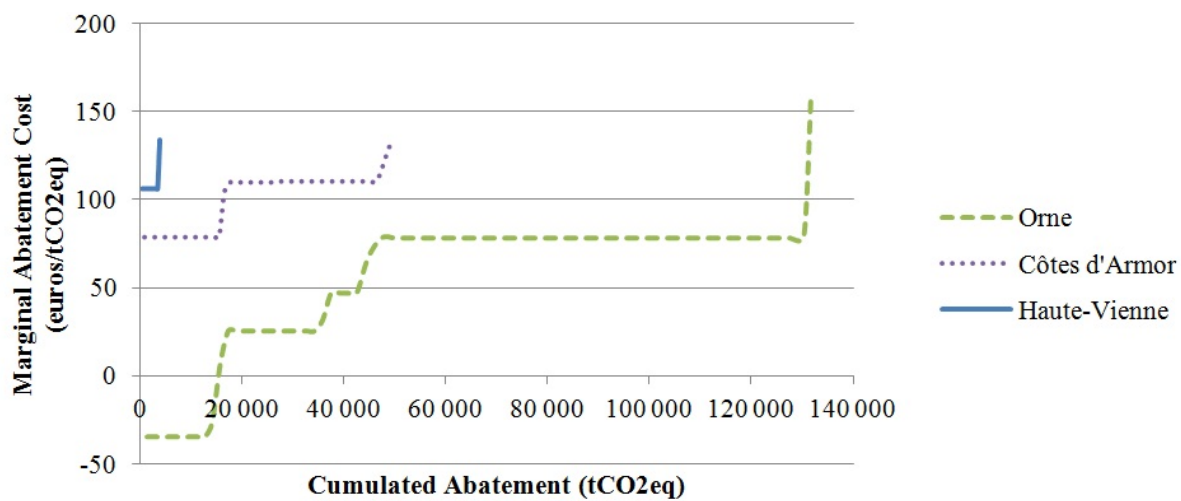
653 Figure 3: Sensitivity of the abatement cost to variable limit (results per year)



654

655 Figure 4: Departmental share of the mitigation potential (in percentage) for a marginal

656 abatement cost of 80 euros/t to reach an overall abatement of 0,9 MtCO<sub>2</sub>eq/year (limit : 50%)

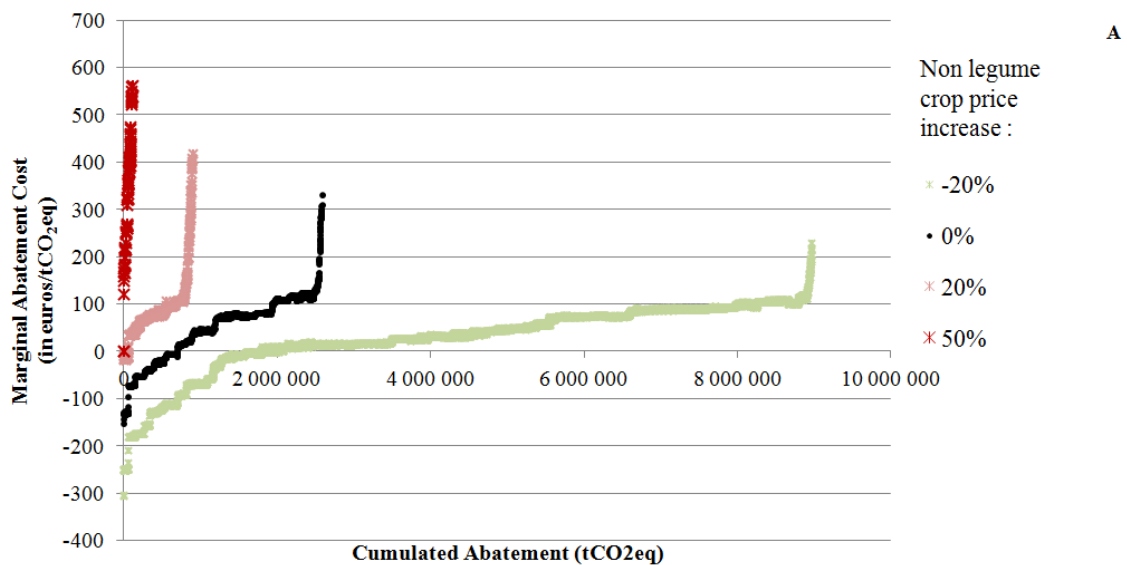


657

658 Figure 5: Examples of marginal abatement cost curves for three geographical areas for one

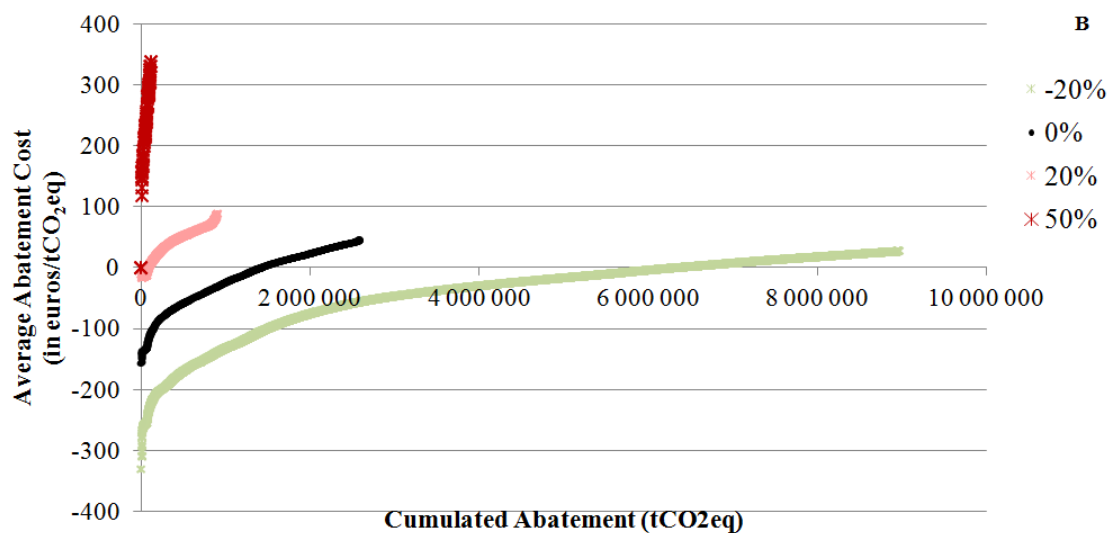
659 year (limit: 50%)

660



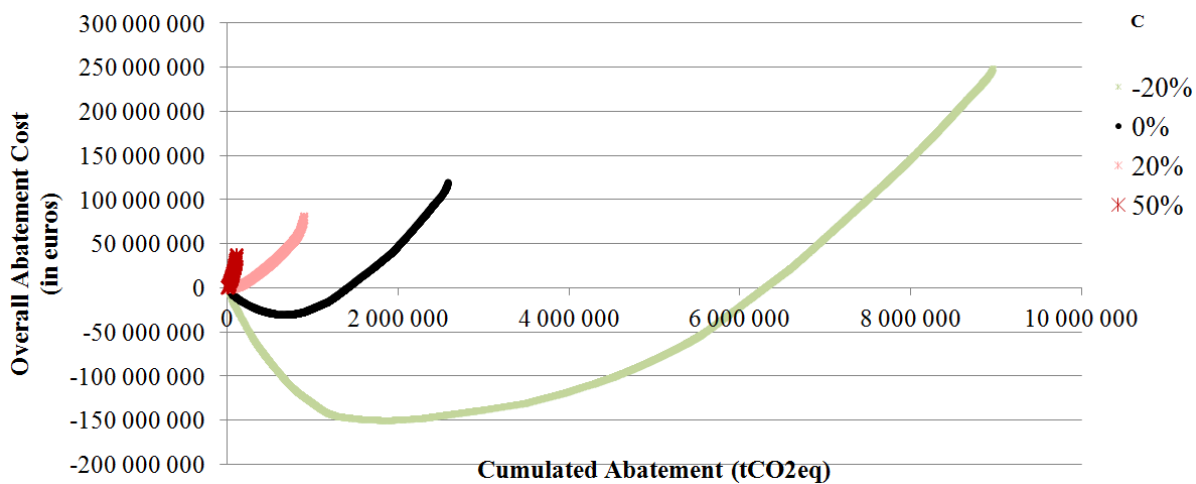
661

662 Figure 6 a



663

664 Figure 6 b



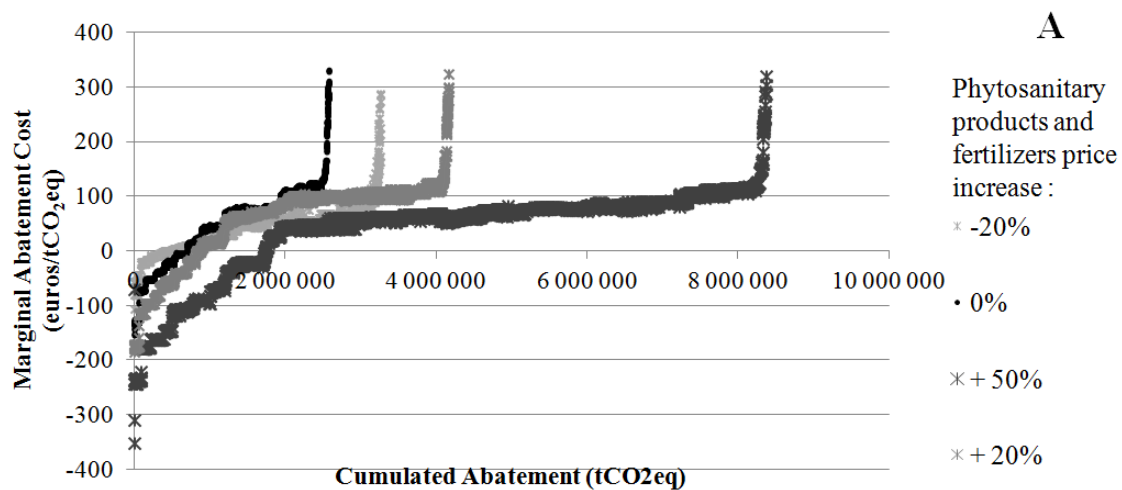
665

666 Figure 6 c

667 Figure 6: Sensitivity of the abatement cost to variation in grain prices (other than legumes)

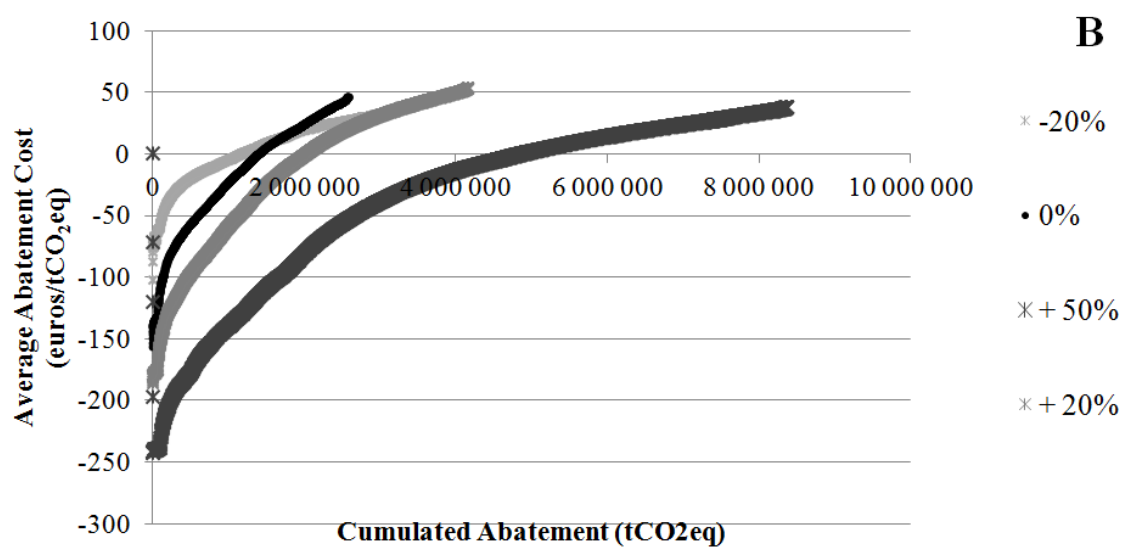
668 (results per year)

669



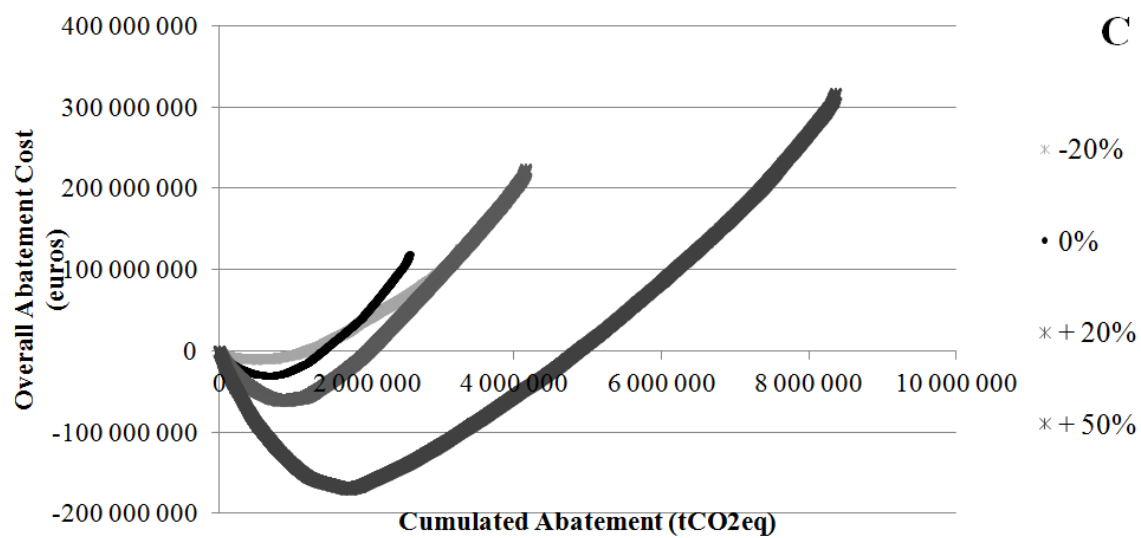
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671 Figure 7 a



672

673 Figure 7 b



674

675 Figure 7 c

676 Figure 7: Sensitivity of the abatement cost to agricultural input prices (results per year)

677

678 **Table**

679 Table 1 – Comparison between the two policy approaches for the same target of abatement

		<b>Uniform doubling across all geographical areas</b>	<b>Carbon Pricing</b>
<b>Final legumes area</b>	<b>Million ha</b>	<b>1,5  (12% of French overall agricultural land)</b>	
<b>Overall Cost</b>	<b>Million euros/year</b>	<b>127</b>	<b>18</b>
<b>Marginal Abatement Cost</b>	<b>Euros/tCO<sub>2</sub>eq</b>	<b>-</b>	<b>80 euros/tCO<sub>2</sub>eq</b>
<b>Overall Abatement</b>	<b>Million tCO<sub>2</sub>eq</b>	<b>1,03</b>	<b>0,9</b>
<b>Average Abatement Cost</b>	<b>Euros/tCO<sub>2</sub>eq</b>	<b>123</b>	<b>19,5</b>

680

681