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The cost of emissions mitigation by legume crops in French agriculture

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Abstract

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

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

1 Introduction

Agriculture accounts for a significant proportion of total greenhouse gas (GHG) emissions both in France and at the European level. In 2011, European Union agriculture accounted for 461 million tCO_2eq, while in France the amount was 92,5 million tCO_2eq (respectively 10,8 and 20,6% of European and French GHG emissions including land use, land use change and forestry according to UNFCCC[1] National Inventory Report, 2013). A recent European Commission communication (European Commission, 2014) on the policy framework for climate and energy indicated that emissions from sectors outside the EU Emission Trading Scheme (EU-ETS) would need to be cut by 30% below the 2005 level by 2030. At the same time, within the framework of the 'energy-climate' package France has committed to reduce emissions of its sectors not covered by the EU-ETS by 14% by 2020 compared to 2005 emissions levels (European Union, 2009).

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

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[1] United Nations Framework Convention on Climate Change.

[2] Calculated by dividing the 20,29 $MtCO_2eq$ emissions from crops (see appendix A) by the 94,3 $MtCO_2eq$ French agricultural emissions (CITEPA, 2012).

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

Legumes (fabaceae), commonly known in France as alfalfa, pea, or bean family, have the ability to naturally fix atmospheric nitrogen and can reduce N_2O emissions compared with conventional crops (maize, wheat, barley, oilseed, rape). This function is conferred by rhizobium bacteria that live in symbiosis at the level of their roots in little organs called nodules. As a consequence, they need far less fertilizer thanks to the fixing effect allowing nitrogen to stay in the ground for up to two years after planting. This contributes additional amounts of nitrogen to subsequent crop in rotations. Studying alternative crop emissions, Jeuffroy et al. (2013) demonstrated that legume crops emit around five to seven times less GHG per unit area compared with other crops. Measuring N_2O fluxes from different crops they show that peas emitted 69 kgN_2O/ha; far less than winter wheat (368 kgN_2O/ha) and rape emissions (534,3 kgN_2O/ha). Moreover, compared to the emissions from cattle meat production, human consumption of peas instead of meat leads to 85 to 210 times less N_2O emissions for the same content of protein ingested[3]. Despite this mitigation benefit, N-fixing crops have low agronomic performance (see appendix A) and consequently their introduction in arable systems will, in most regions, incur a penalty in terms of farm revenue.

Recent research (Pellerin et al. 2013) has suggested the cost of GHG mitigation via grain legumes at around 19 euros/tCO_2eq. This paper scrutinises this assessment by proposing three

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[3] 20-37 gN_2O/kg protein for meat and 0,17-0,23 gN_2O/kg protein for peas. The amount of emissions for meat is obtained using the N_2O content from feed fertilization and manure management included in cattle meat from Dollé *et al.* (2011) of 3,026 kgCO_2eq and 1,615 kgCO_2eq 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 Ciqual (2012).

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

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

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

2 Context

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[4] 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.

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

This decline is due to several factors. First an increasingly meat-based diet incorporating less vegetable proteins led to lower consumption of legumes by humans. The General Commission for Sustainable Development reports that in France between 1920 and 1985 human seed legume consumption fell from 7,3 kg/person/year to 1,4 kg/person/year (Cavaillès, 2009). This trend coincided with a change in livestock feeding regimes, with legume-based rations being increasingly replaced by maize silage, grass plants and imported soybean meal. The loss of agricultural nitrogen due to this switch in farmlands was compensated by chemical fertilizers, which had become increasingly price-competitive since the 1960’s. Simultaneously, trade agreements on the abolition of customs tariffs between Europe and the United States favored American soybean imports. Finally, a lack of agronomic research dedicated to legumes compared with common crops, led to a relative decrease of their agronomic performance (Cavaillès, 2009).

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

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[5] http://faostat.fao.org/

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

3 Cost-effectiveness analysis in the literature

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

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

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

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

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

CO_2 equivalent mitigation is the same for each specific option irrespective of spatial scale or in terms of the overall volume of emission reduction, which would seem unlikely. Indeed, due to regional variability in soils, farm systems, climate and yields, abatement cost would also vary for any individual mitigation measure.

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

Legumes have been specifically assessed in a UK study constructing a national MACC for agricultural GHG emissions (Moran et al., 2010). The marginal abatement cost obtained for legume crops appears constant and very high (14280 £/tCO_2eq equivalent to 17000 euros/tCO_2eq). This is in stark contrast to Pellerin et al. (2013) estimate of only 19 euros/t CO_2eq. To explore some of the reasons for this disparity we adopt a predominantly engineering approach combined with elements of an economic approach to explore the role of farm systems decision-making around the adoption of legumes as a specific measure that can influence farm profitability.

4 Method

4.1 Defining emissions and gross margin

The analysis assesses the abatement potential in 96 French metropolitan geographical areas, each considered as a single farm decision unit. The analysis is confined to the within farm gate effects and does not account for the upstream or downstream impacts; e.g. associated with lower fertilizer production, or the emission mitigation benefit related to enteric fermentation of cattle consuming legumes (McCaughey et al., 1999). In each geographical area, farmland emissions and profits are calculated and decomposed for each crop (Common Wheat, Durum Wheat, Barley, Maize, Sunflower, Rapeseed, Pea, Horse bean and Alfalfa).

We followed the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) to estimate N_2O emissions per hectare. Using mineral nitrogen spreading rates and organic spreading rates from the Agricultural Practices survey (Agreste, 2010) we calculate the following kinds of emission sources:

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

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

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

Where $GM_{k,i}$ is the gross margin calculation for each crop i in each geographical area k (in euro per ha). $Price_{k,i}$ is the crop price in euros per ton and $yield_{k,i}$ is expressed in tons per hectare. The expenses in phytosanytary products ($exp_{phyto,k,i}$), in fertilizers spread ($exp_{ferti,k,i}$) and in seed ($exp_{seed,k,i}$) are all measured in euros per hectare.

4.2. Baseline

Appendix A shows the results for the main crops cultivated in France and gives the baseline for overall farmland gross margin (6,4 billion euros) and for emissions (20,4 $MtCO_2eq$). When comparing these emissions with those of the national inventory report, we observe that the amount represents less than half of the category 'Agricultural Soils' (46,7 $MtCO_2eq$ (CITEPA, 2012)). This category represents all N_2O emissions linked to soil fertilization both from cropland and grassland soils. Hence the baseline emissions assessed here is quite coherent since we only focus here on emissions from croplands which represent less than half of the French Utilized Land Area[6].

4.3. Introduction of legumes onto croplands

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

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

$$Marginal\ Abatement\ Cost = \frac{dCost}{dEmissions}$$

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[6] 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.

Legume substitution continues until a marginal abatement cost of 125 euros/tCO_2eq has been exceeded per geographical area. This upper abatement cost threshold has been arbitrarily chosen, considering the relative abatement cost in other sectors (Vermont and De Cara, 2014)[7].

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

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[7] Vermont and De Cara, 2014 assesses for instance a marginal abatement cost curve for European farms until a maximum level of 100 euros/tCO_2eq

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

As legume crops are introduced onto farmland the cumulated cost corresponds to the sum of dCost and the cumulated abatement corresponds to the sum of dEmissions generated at each additional area introduction. These cumulated cost and abatement are obtained both at the regional and national levels. The average mitigation cost is the ratio between cumulated cost and cumulated abatement. Figure 1 illustrates a sample geographical area in which legumes area is increased with a 50% limit. Agricultural land is allocated with only 5 crops, each characterized by a specific emissions rate per hectare and gross margin. Assume the rank of crops considering their ratios of gross margin per emissions is : crop i, crop j, crop l and crop m. Thus, the additional area of legumes first replaces crops i. Once crop i has lost 50% of its area, legumes replace crop j, and so on until the introduction reaches crop m. At this stage, the 125 euros/tCO_2eq is achieved, which consequently stops further legume introduction.

[Figure 1]

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

[Figure 2]

5 Results

5.1 Abatement potentials and cost

At the national level and assuming the variable limit of 100%, the maximum technical abatement of 2,5 million tCO_2eq/year is possible for an overall cost of 118 million euros/year (see figure 3. c). This corresponds to an increase of 1,6 Mha of legumes and an average abatement cost of 43 euros/tCO_2eq.

The overall cost depends on the volume of emissions reduction. Since displaced crops in each geographical area are ordered by their ratio of gross margin per emission, the lower the abatement targets the lower the overall cost. For example, if the target of emission reduction is reduced by 30%, to 1,7 $MtCO_2eq$, the average abatement cost is reduced by 80% to 14 euros/tCO_2eq. If the target is lower than 1,4 $MtCO_2eq$, we find a negative abatement cost, implying that legumes are actually now more profitable than the crop that is displaced .

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

Pellerin et al. (2013) suggests that legume introduction could provide an overall abatement potential of 0,9 $MtCO_2eq$, at a cost of 17 million euros. This implies an average mitigation cost of 19 euros/tCO_2eq. That study did not consider how cost varies with area and hence the potential for negative costs. By illustrating those results (the blue curve in Figures 3b and 3c) alongside those derived in this study, it is possible to see that defining a variable limit of 50%, which is the average scenario, and the most realistic, for the same amount of emission abated, we obtain the same overall cost and the same average abatement cost (reached for a marginal abatement cost of 80 euros/tCO_2eq).

[Figure 3 a]

[Figure 3 b]

[Figure 3 c]

5.2 Heterogeneity of abatement cost between French geographical areas

The spatial allocation of the abatement potential between different geographical areas can be represented for the same marginal abatement cost. Figure 4 shows the departmental shares for the same marginal carbon reduction cost threshold (80 euros/tCO_2eq) and a 50% limit to achieve the same reduction estimated by Pellerin et al. (2013). The results show considerable geographical variability, with some accounting for a small amount of the 0,9 MtCO_2eq national abatement. These geographical areas are mainly located in the south and eastern parts of France, and represent each less than 1% of these overall reduced emissions. Departments with the highest potential are located in the north-west, where the majority of the geographical areas represent each more than 1% of the national abatement. Note that two regions, Orne and Manche, can each contribute more than 10% of the national abatement.

An alternative representation of the cost heterogeneity is presented in figure 5 for three geographical areas: Orne, Haute-Vienne and Côtes d'Armor. Introducing legumes in Orne is more profitable than in Haute-Vienne or in Côtes d'Armor. In the latter two regions, even for low levels of mitigation the marginal abatement cost is high (respectively 80 euros/tCO_2eq and 110 euros/tCO_2eq). This cost heterogeneity demonstrates the challenge of setting a uniform nationwide target. If, for example the objective of reducing 50 000 tCO_2eq GHG emissions were assigned for the three previously mentioned geographical areas, the overall cost would be high relative to the case of one region (Orne), mitigating 130 000 tCO_2eq on its own. As a result, this simulation demonstrates the advantages of policy instruments that account for the cost heterogeneity between regions.

[Figure 4]

[Figure 5]

5.3 Sensitivity analysis

Figure 6 shows the impact on the abatement cost of price variations of conventional crops. When seed prices of alternative crops increase, the opportunity cost of legume introduction rises. On the contrary, when seed prices decrease, the difference of gross margin between legumes and conventional crops decreases as well and makes their introduction less costly. We represent the abatement curves for the follow price increases: -20%, +20% and +50%. For a price decrease of -20%, negative abatement costs appear until an abatement level of 6 $MtCO_2eq$. For a price increase of 20%, the opportunity of decreasing emissions while increasing profit disappears completely. The abatement cost becomes considerably high when the increase is 50%. Consequently, we observe a strong sensitivity of abatement cost to the price of conventional crops.

Abatement costs are also highly sensitive to agricultural input prices (fertilizers, seeds and phytosanitary products) (figure 7). A rise of 20% of input prices compared to baseline values determined in the Ecophyto R&D (2009) favors legume introduction by lowering the abatement cost. A higher increase of 50% for a marginal abatement cost of 30 euros/tCO_2eq increases the abatement from 0,8 to 2 million tons CO_2 equivalent. On markets, input prices are not so volatile. Although they rose sharply in 2008-2009, this spike was exceptional relative to recent trends showing more stable increases. The prospect of rising fossil fuel prices, which are inputs to phytosanitary products manufacturing, suggests that the opportunity cost of legumes may be lower in the future.

[Figure 6 a]

[Figure 6 b]

[Figure 6 c]

[Figure 7 a]

[Figure 7 b]

[Figure 7 c]

6. Discussion

A problematic observation in the analysis is the presence of negative abatement costs, which raises questions about their veracity. Specifically, it is unclear why farmers would not automatically adopt such profitable measures (and provide associated mitigation) unless it is the case that there are other unaccounted for costs driving decision-making, which are not captured in this analysis. These hidden costs can be attributed to a variety of barriers within and beyond the farm. Some barriers are intrinsic to individual behaviors and imply internal factors (cognition and habit) and social factors (norms and roles) (Moran et al. 2013). Moreover, farmers may be exhibiting risk aversion behavior in response to legume yield variation. In this study, the average legume gross margin is relatively high in some regions, making the crop in rotations more profitable than some of the conventional crops. However, the annual yield of legume disguises significant annual variation that is not represented here. Consequently some farmers, actually grow crops with a lower gross margin to be sure that the yield of the crop will be high enough and to avoid any risk of significant loss associated to legumes. This risk aversion is also linked to the volatility of other crop prices, which has a strong impact on abatement cost as shown in figure 5. Furthermore, as noted by Gouldson (2008), some factors are external to the farm. These include a necessity to adapt the organization of agricultural cooperatives to collect the output of legumes. For instance, legumes need adapted silos that are not currently established in all regions in France. The role of cooperatives is also important in the diffusion of information, training and advice in the agricultural sector (Meynard et al., 2013).

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

The fact that abatement costs vary strongly from one geographical area to another suggests that these instruments should rely more on market-based approaches, rather than a regulatory approach aimed at increasing legumes area directly. Such approaches (e.g. a tax or forms of emissions permits) offer the flexibility of response, thereby increasing the likelihood of realizing the abatement potential identified by marginal abatement cost curves. Specifically, when a carbon price is implemented in a specific sector, agents should reduce their emission until the marginal abatement cost reaches the carbon price (de Perthuis et al., 2010).

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

For illustration, we compare the two approaches for the same target for increasing legumes (doubling the current area at national level). This target is chosen since it corresponds to an area that should be cultivated in France to reduce dependence on soya imports (Cavaillès, 2009). In the carbon pricing approach, a doubling of legumes at national level happens at a carbon price of 80 euros/tCO_2eq. In the uniform regulatory approach, each geographical area is required to double its legumes area. On the face of it, the latter approach appears logical if we consider that each region increases area in proportion of the initial area. Yet, we observe in table 1 that for the same target, the overall abatement cost is far lower under a carbon price (18 million euros) than under a uniform target (127 million euros).

An experimental initiative with offset payments for legume cultivation is currently being piloted on a voluntary basis by some regional cooperatives (InVivo, 2011). Farmers willing to increase the share of legumes on their land receive a carbon annuity, determined by the level of carbon price on the EU ETS[8]. However, few cooperatives have been part of this initiative. Indeed, the carbon price being relatively low at 5 euros/tCO_2eq (CDC Climat, 2014) the offer is not attractive for farmers. An advantage of the MACC analysis presented here is to assess the impact on abatement if this initiative were to become more widespread, subsequently to higher carbon price level.

[Table 1]

7. Conclusion

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

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

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[8] This project is led under the framework of the Joint Implementation (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.

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

An interesting addition to this work would be to investigate the upstream and downstream impact of legume on greenhouse gases and their consequences on abatement cost. The production of chemical fertilizers is responsible for significant CO_2 emissions in industries. Hence, the associated decrease of emissions due to chemical fertilizers substitution should decrease abatement cost. Further, the displacement of imported soybean by fodder legumes such as alfalfa would have a positive impact on enteric fermentation, responsible for methane emissions in livestock feeding regimes (Martin et al., 2006). It would also via indirect land use change (De Cara, 2013) impact land use emissions of countries where soybean is currently produced. Accordingly, studying impacts beyond the farm gate would be a useful extension.

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

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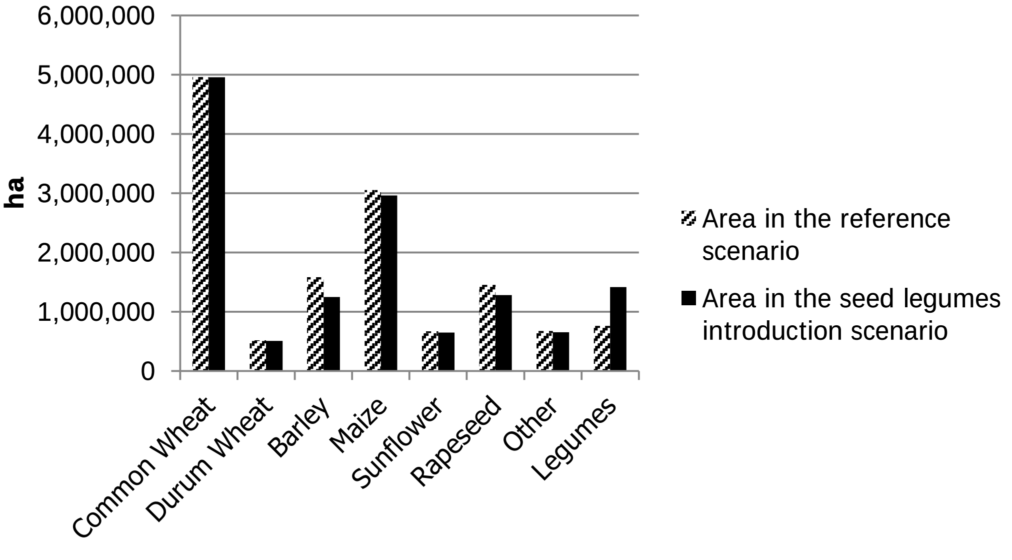
Appendix A – Area, emissions and gross margin for the main crops in France at the national level in the baseline situation

	Area	**Average Emissions**	**Overall Emissions**	**Average GM**	**Profit**
	ha	**kgCO$_2$eq/ha**	**MtCO$_2$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
All Crops	**13 673 738**	**-**	**20,29**	**-**	**6 372,90**

Appendix B – Impact on legume introduction on other cereals area (for a carbon price of 80 euros/tCO$_2$eq with a limit of 50%)



Figures

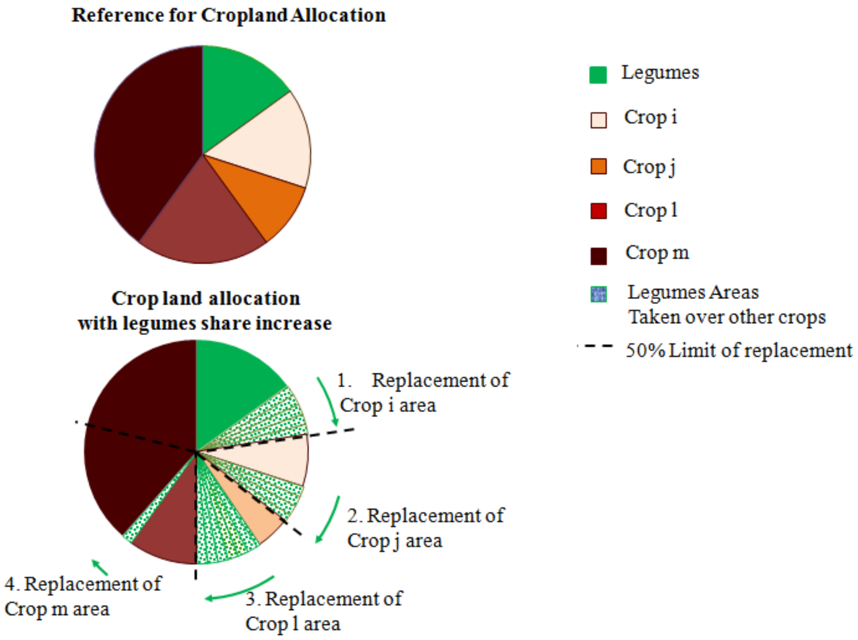


Figure 1: Illustration of legume area increase in farmlands at the departmental scale

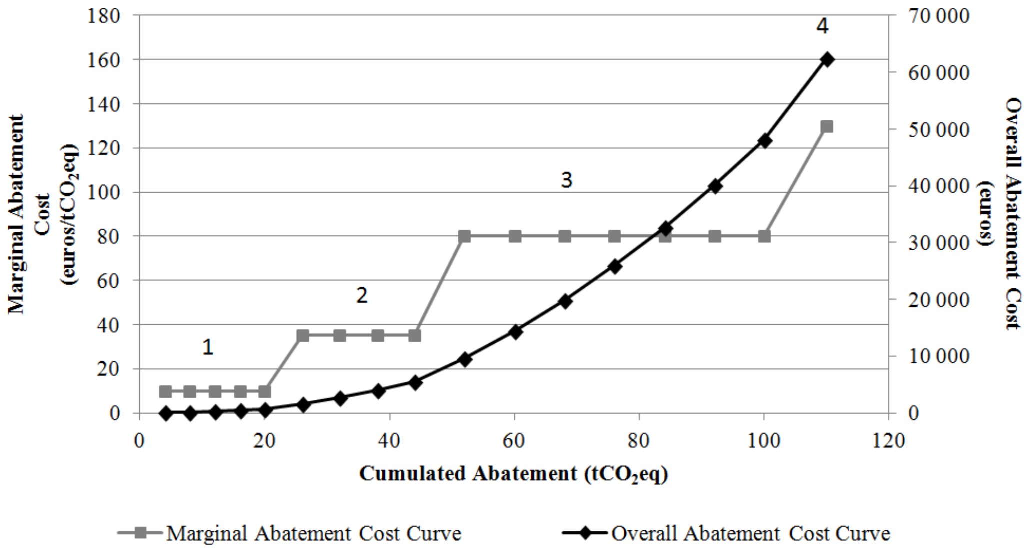


Figure 2: Illustrative marginal and overall abatement cost curves linked to increasing legume area on farmland

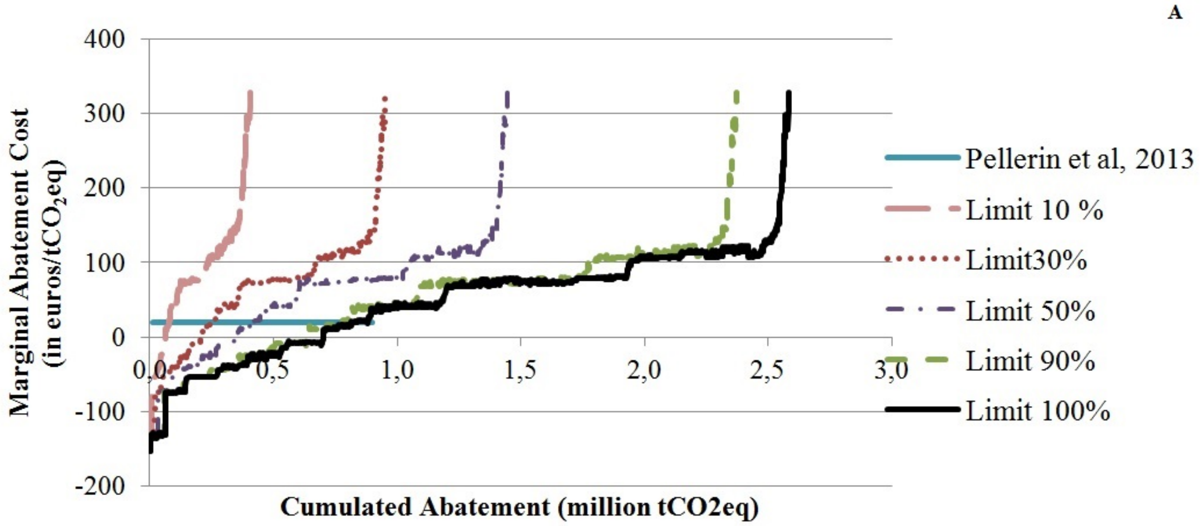


Figure 3 a

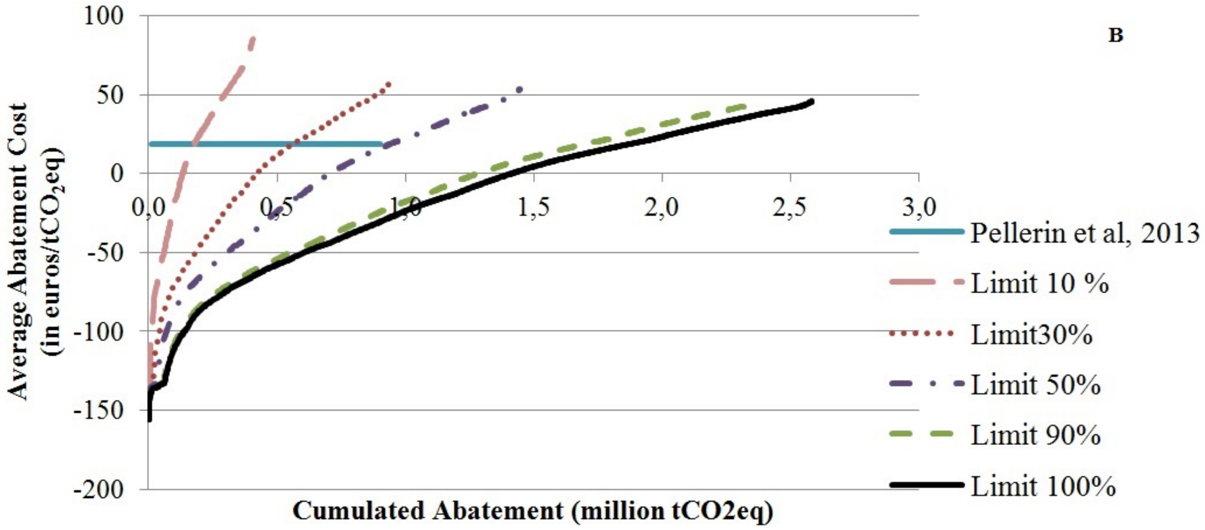


Figure 3 b

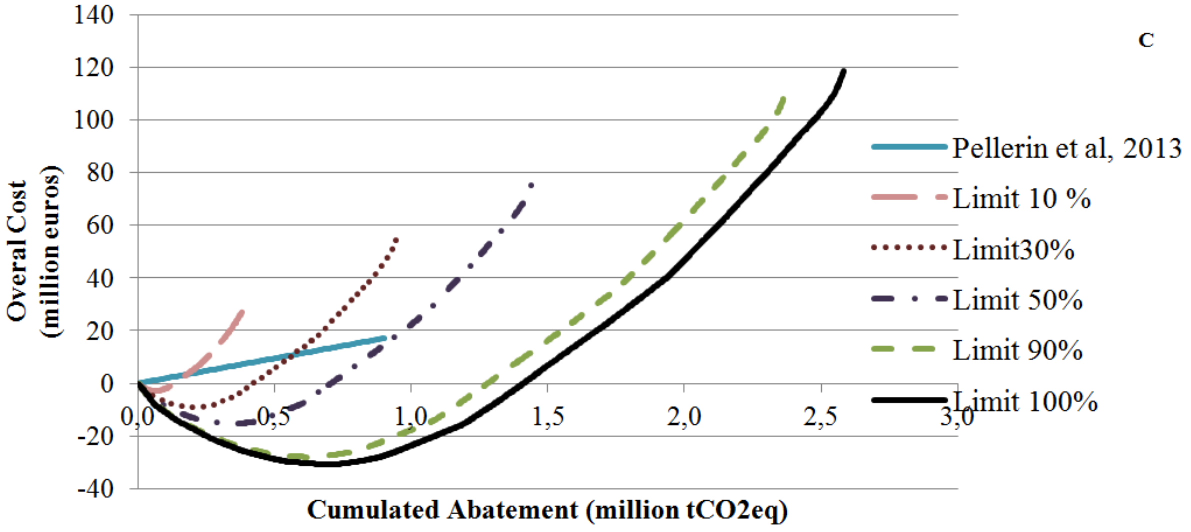


Figure 3 c

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

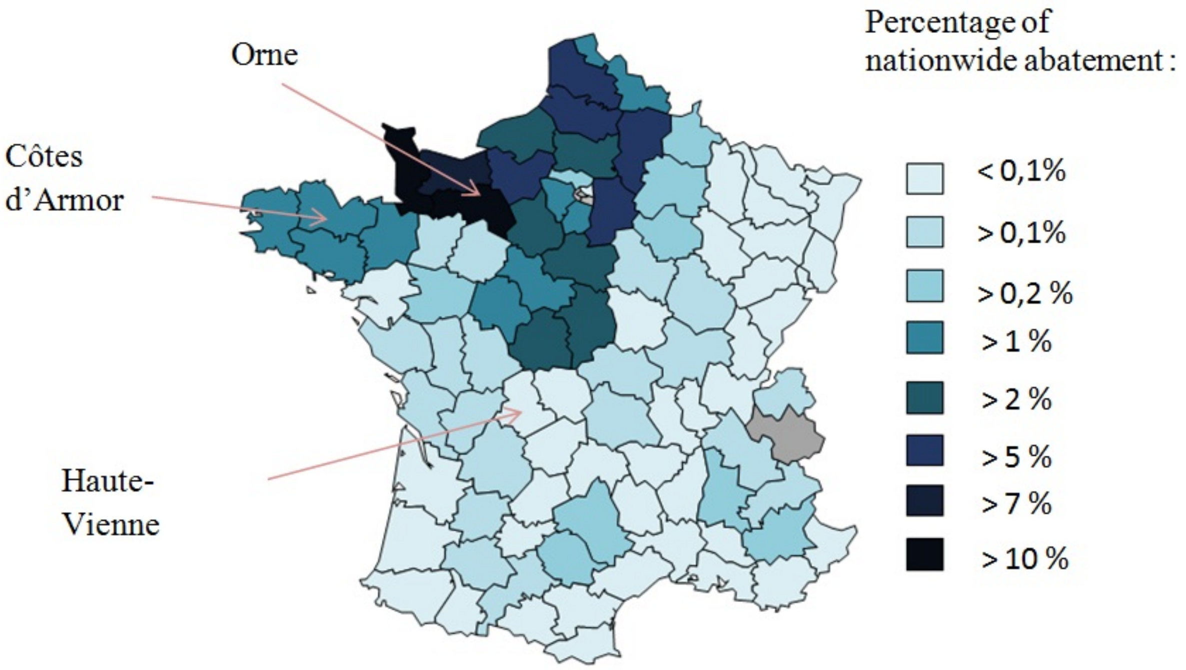


Figure 4: Departmental share of the mitigation potential (in percentage) for a marginal abatement cost of 80 euros/t to reach an overall abatement of 0,9 MtCO2eq/year (limit : 50%)

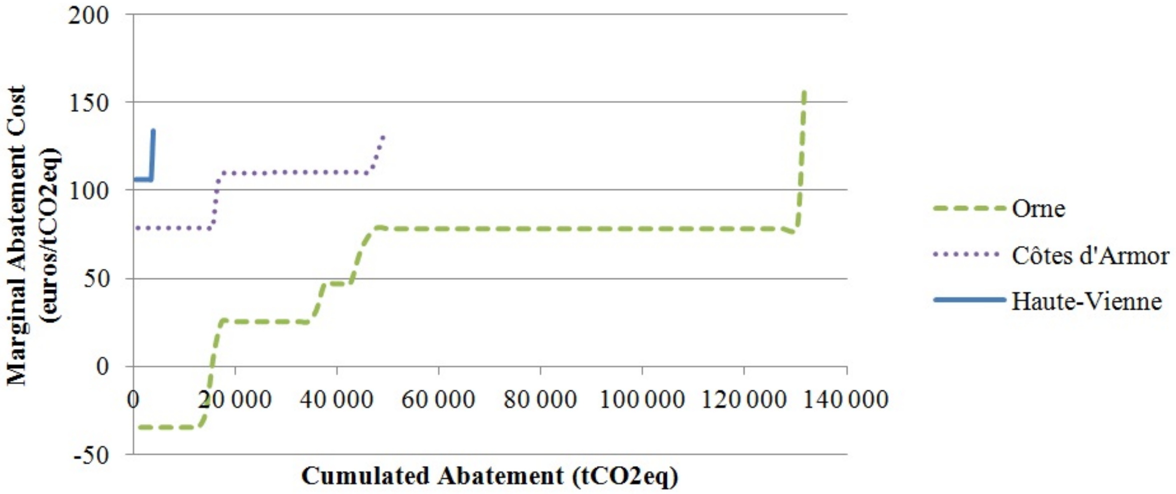


Figure 5: Examples of marginal abatement cost curves for three geographical areas for one year (limit: 50%)

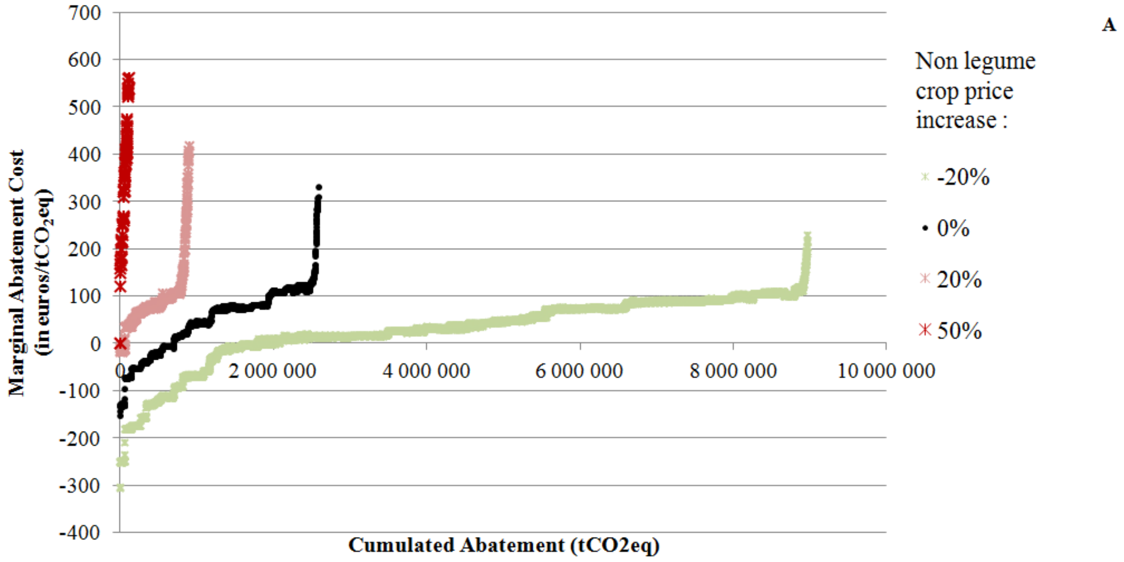

A
Marginal Abatement Cost (in euros/tCO$_2$eq)
700
600
500
400
300
200
100
0
-100
-200
-300
-400
0
2 000 000
4 000 000
6 000 000
8 000 000
10 000 000
Cumulated Abatement (tCO2eq)
Non legume crop price increase :
-20%
0%
20%
50%

Figure 6 a

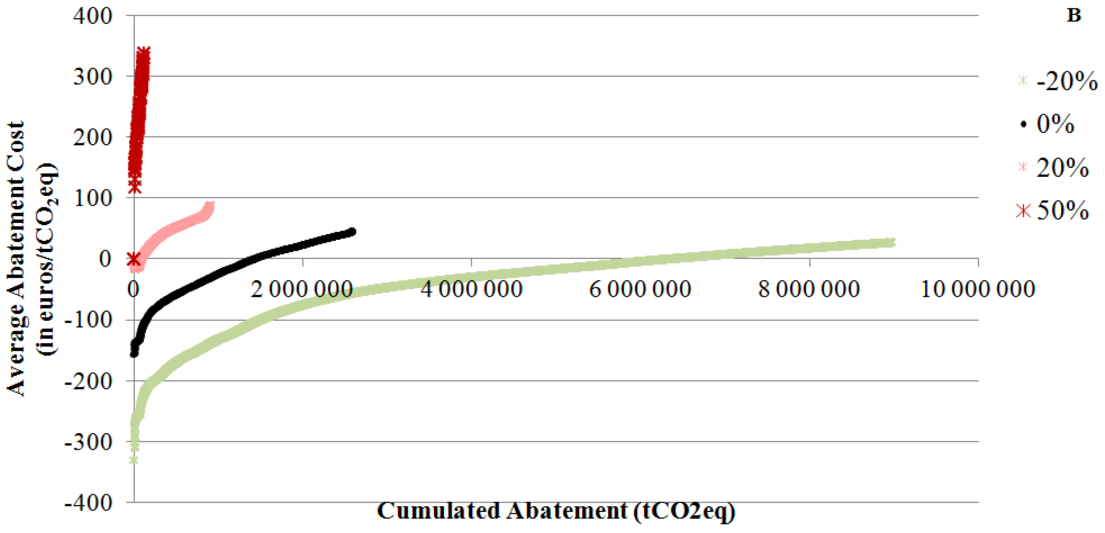

B
Average Abatement Cost (in euros/tCO$_2$eq)
400
300
200
100
0
-100
-200
-300
-400
0
2 000 000
4 000 000
6 000 000
8 000 000
10 000 000
Cumulated Abatement (tCO2eq)
-20%
0%
20%
50%

Figure 6 b

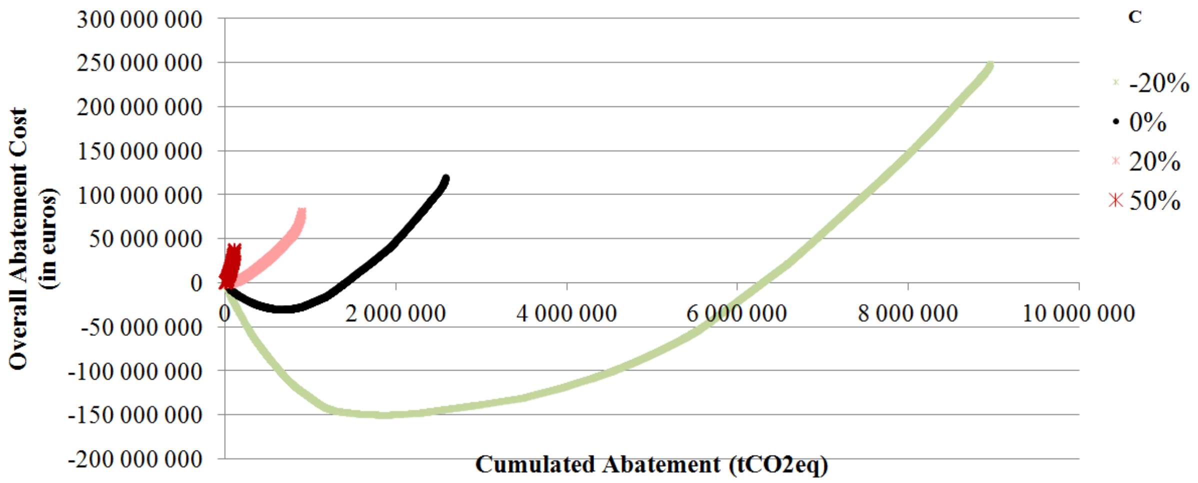
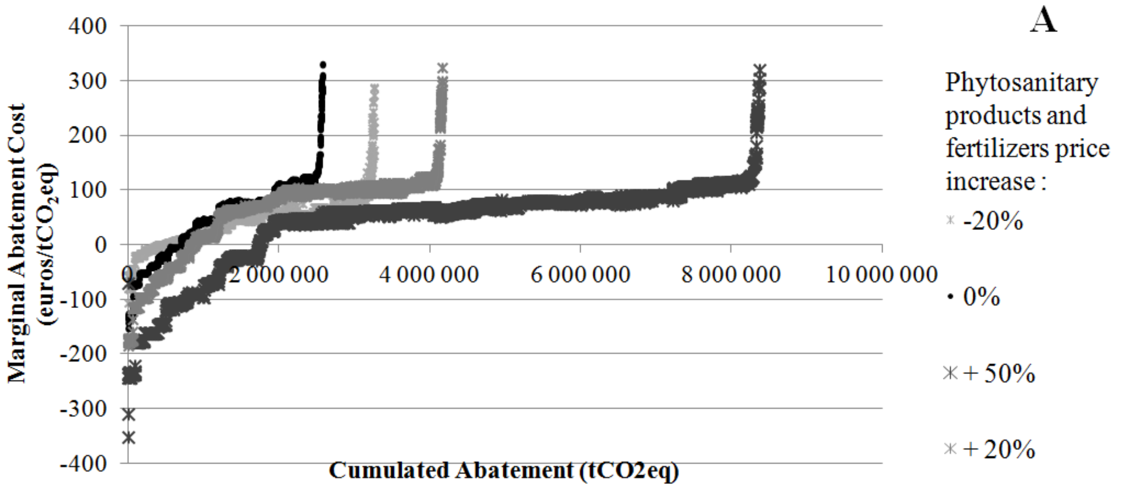
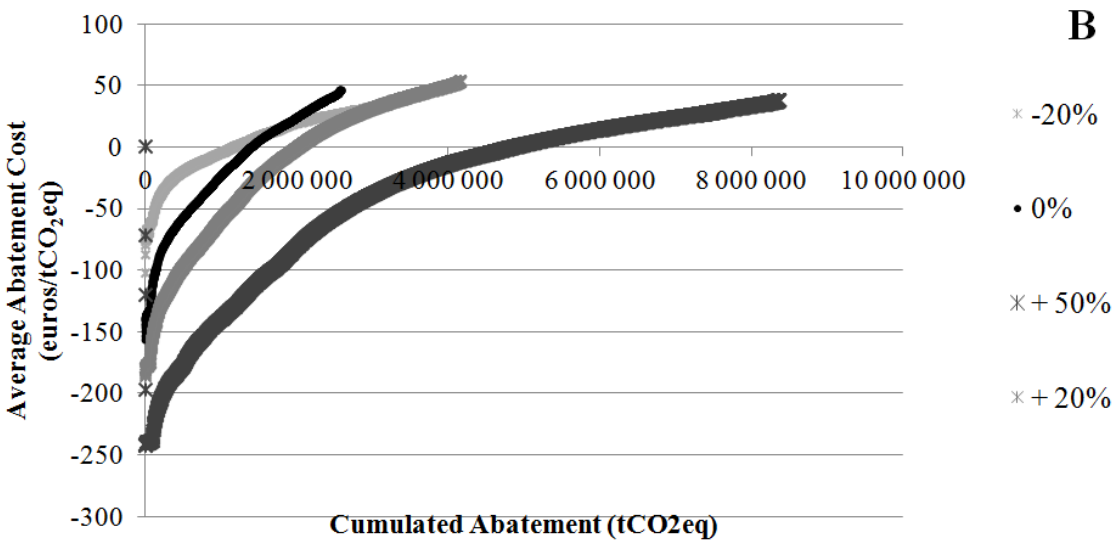


Figure 6 c

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



671 Figure 7 a



673 Figure 7 b

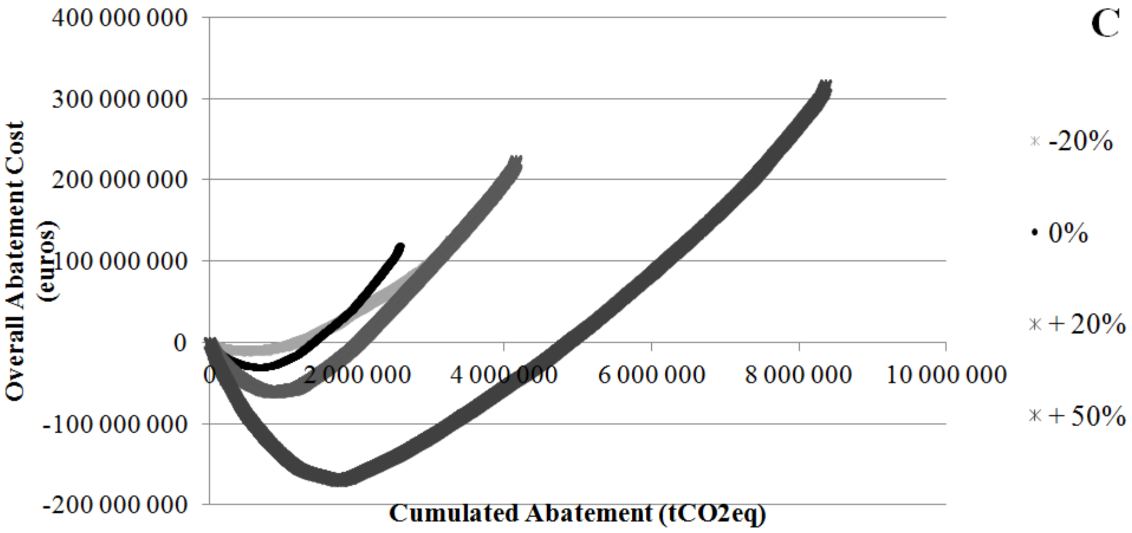


Figure 7 c

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

Table

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

		Uniform doubling across all geographical areas	**Carbon Pricing**
Final legumes area	**Million ha**	**1,5** **(12% of French overall agricultural land)**	
Overall Cost	**Million euros/year**	**127**	**18**
Marginal Abatement Cost	**Euros/tCO_2eq**	**-**	**80 euros/tCO_2eq**
Overall Abatement	**Million tCO_2eq**	**1,03**	**0,9**
Average Abatement Cost	**Euros/tCO_2eq**	**123**	**19,5**