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Identifying cost-competitive greenhouse gas mitigation potential of French agriculture

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Abstract

The agriculture, forestry and other land use sector is responsible for 24% (10-12 Pg CO_2e per year) of anthropogenic greenhouse gas (GHG) emissions worldwide, with concomitant opportunities for mitigation. A scientific panel used deliberative methods to identify ten technical measures comprising 26 sub-measures to reduce GHG emissions from agriculture in France. Their abatement potential and cost are compared. The proposed measures concern nitrogen (N) management, management practices that increase carbon stocks in soils and biomass, livestock diets, and energy production and consumption on farms. Results show that the total abatement potential can be divided into three parts. One third of the cumulated abatement potential corresponds to sub-measures that can be implemented at a negative technical cost. These sub-measures focus on increased efficiency in input use including N fertilisers, animal feed and energy. The second third are sub-measures with moderate cost (< €25 per metric Mg of avoided CO_2e). These sub-measures require specific investments or changes to cropping systems, but additional costs or lower incomes are partially compensated for by a reduction in other costs or by the production of other marketable products. The remaining third are high-cost sub-measures (> €25 per metric Mg of avoided CO_2e). These require investment with no direct financial return, the purchase of particular inputs, dedicated labour time or involve production losses. Assuming additivity, the cumulated abatement is 32.3 Tg CO_2e per year in 2030, but only 10 Tg (i.e. 10% of current agricultural emissions) when calculated under current inventory rules. This study confirms that a significant abatement potential exists in the agricultural sector, with two thirds of this potential at low or even negative cost. This is likely to be an underestimated as it is based on a status quo of the current agricultural system. Results also emphasise the need to upgrade inventory rules so that efforts to reduce emissions can be accounted for.

Keywords

Greenhouse gas, agriculture, mitigation measures, marginal abatement costs

1. Introduction

Agriculture, forestry and other land use (AFOLU) is responsible for 24% (10-12 Pg CO_2e per year) of greenhouse gas (GHG) emissions worldwide (Smith et al., 2014). Of this, 12% is caused by land use and land use changes, including deforestation and draining peat, mainly as CO_2; 7% is due to methane (CH_4) produced by ruminants and by anaerobic fermentation of organic matter, especially in saturated soils such as paddy fields; and 5% is due to nitrous oxide (N_2O) produced by biochemical nitrification and denitrification reactions in soils and manures. One particular feature of agricultural emissions is that they are mainly not related to energy but are controlled by diffuse biological processes.

Agriculture can contribute to international and national GHG reduction objectives using three levers: reducing N_2O, CH_4 and CO_2 emissions, storing more carbon in soil and biomass and producing bioenergy (biofuels, biogas) to replace fossil energies, thereby reducing emissions by a substitution effect. Many mitigation measures have been proposed at the global scale or for specific countries, agricultural sectors or gases, sometimes associated with rough estimates of their abatement potential (e.g. Cole et al., 1997; Smith et al., 2008, 2013 at the global scale; Aertsens et al., 2013 at the continental scale; Schneider et al., 2007; Fitton et al., 2011; Rees et al., 2013 at the national scale; Monteny et al., 2006; Schils et al., 2013 for the livestock sector; Sommers and Bossio, 2014 for organic carbon storage in soils; Zomer et al., 2016 for agroforestry). However, because of the mainly diffuse nature of the emissions, the complexity of the underlying biophysical and behavioural processes and the huge variability of production systems, the potential for abatement is less precisely quantified in the agricultural sector than in other sectors. Yet, for policy-making purposes, it is essential to accurately assess and compare the cost of the numerous available levers.

Vermont and De Cara (2010) identified three main approaches to assess mitigation costs and abatement potentials: (i) top-down economic models representing the functioning of the agricultural sector and markets at the global scale and at a country/regional resolution, (ii) supply-side sector micro-economic models based on representative farms, and (iii) bottom-up approaches assessing the potential and costs of a set of individual mitigation measures or practices. The two first approaches focus on the impacts of a carbon price on abatement potential, whereas the latter approach enables a more detailed or “engineering” assessment of technological mitigation measures. A typical output of these studies is a marginal abatement cost curve (MACC), which ranks the measures or practices by increasing mitigation cost along with their mitigation potential. Examples of the use of this approach in a number of national contexts can be found in MacLeod et al., 2010; Moran et al., 2011 for the UK; O’Brien et al., 2014 for Ireland; Wang et al., 2014 for China. Bottom-up engineering are typically based on a two-step process, first, screening candidate measures to select the most relevant ones in the agricultural context concerned, and second, detailed calculations of their potential abatement and cost. Existing studies are limited in that they often consider both short-term technical options which can be implemented immediately, like fertilisation or tillage management practices, and long-term levers that require further investments and research, like crop or animal breeding based on new selection criteria. Considering all categories of measures together may be confusing for policy making purposes since they do not use the same time scales or address the same end-users. Moreover, in addition to the challenges of calculating abatement potential and costs, O’Brien et al. (2014) pointed out that the outcomes of such studies are highly dependent on the method used to calculate the abatement, i.e. the IPCC-national inventory approach or a life cycle assessment approach. Most studies use the IPCC-national inventory approach, so that the proposed mitigation options to reduce emissions from the national agricultural sector may inadvertently increase global emissions because of the effects they have elsewhere in the world (Franks and Hadingham, 2012). Therefore, a clear distinction must be made between direct emissions (occurring on the farm), indirect emissions (occurring outside the farm, after physical transfer of molecules) and emissions induced upstream or downstream of the farm, through the purchase or sale of goods or services.

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

2. Methods

2.1 Pre-selection of the proposed measures and sub-measures

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

An initial step screened around 100 mitigation measures, reorganised in 35 categories, which were found in the literature and used as a starting point for this study. Five criteria were used to shortlist 10 measures from this preliminary set:
The measure must be linked to an agricultural practice potentially chosen by the farmer, with at least part of the expected abatement located on the farm, requiring no major modification to the production system and with no reduction in yields exceeding -10%. Any measures targeting a sector upstream or downstream of the farm (e.g. human diets) or the agricultural sector, but with a mainly upstream or downstream effect (e.g. energy crops), or involving major changes in the production system (e.g. a change from conventional to organic farming) or having an excessively negative effect on production volumes (e.g. livestock reduction), were considered to be beyond the scope of the study.

Measures whose abatement potential was judged to be low or uncertain were rejected. A potential was judged to be low either due to a modest unitary abatement and/or because the potential applicability of the measure, i.e. the surface areas or livestock numbers on which the application of the measure was technically possible, is limited in the French agricultural context (e.g. measures concerning paddy fields, which represent 0.06% of the agricultural area in France). This preliminary assessment of the mitigation potential of each measure was based on results in the literature. For the 10 measures ultimately short-listed, this potential was calculated more precisely in the second step of the study.

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

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

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

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

2.2 Calculations

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

2.2.1 Greenhouse gas emissions unitary abatement potential

The unitary measure abatement potential (per hectare, per head of cattle) was calculated by reviewing all the sources of GHG emissions possibly affected by the measure concerned.
A distinction was made between direct (produced on the farm) and indirect emissions (occurring in the vicinity after physical transfer of molecules, for example nitrate leaching or ammonia volatilization) and induced emissions, which occur upstream or downstream of the farm, linked to changes in the purchase or sale of goods resulting from the measure (e.g. CO_2 emissions associated with the production of N fertilisers or avoided by the sale of renewable energy produced on the farm). Effects of management practices on radiative forcing through albedo were not considered.
As far as possible, calculations were performed using peer-reviewed references, including IPCC guidelines (IPCC, 2006) or modified based on references obtained in the French agricultural context. The unitary abatement was calculated for the three main gases (N_2O, CH_4 and CO_2), and then expressed in equivalent CO_2 (CO_2e) using the 100-year global warming

potential values (GWPs) published in 2006 (298 for N_2O, 25 for CH_4, 1 for CO_2) (IPCC, 2006). Thus, unitary abatements were expressed in kg CO_2e avoided per year and per unit, the unit depending on the sub-measure (hectare, animal, etc.) concerned. For comparison, a calculation based on current national inventory rules, using 1996 IPCC guidelines, was also performed (data not shown).

2.2.2 Unitary cost of the measure for the farmer

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

2.2.3 Potential applicability of the measure and adoption scenario

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

2.3 Marginal abatement cost curves (MACC)

A bottom-up MACC method was used for the inter-comparison of the 26 sub-measures. The two most widely used variables to compare abatement measures are the annual abatement potential and the cost per metric Mg of avoided CO_2e. The annual abatement was calculated by multiplying the unitary abatement potential of each sub-measure by the potential applicability achieved in 2030. The cost per metric Mg of CO_2e avoided was calculated as the ratio of unitary cost to unitary abatement.

3. Results

3.1 Abatement potential and cost of the 26 sub-measures

Figure 1 shows the cost to the farmer of the metric Mg of avoided CO_2e (y axis) versus the annual GHG emissions abatement (x axis) for the 26 sub-measures ranked by increasing cost. Negative costs correspond to a gain for the farmer, generally linked to savings on inputs (so-called win-win measures), while positive costs represent a shortfall. Estimated costs range from – 515 € to + 530 € per metric Mg CO_2e avoided. Annual abatements range from 0.08 Tg CO_2e y^{-1} (energy savings in greenhouses, a sub-measure which is already widely used) to 5.78 Tg CO_2e y^{-1} (methanisation, a sub-measure which was only marginally applied in France in 2010, but has high potential applicability). Assuming additivity, the cumulated abatement is 32.3 Tg CO_2e per year. Considering interactions between sub-measures (e.g. if N fertilisation rates of non-legume crops are reduced, then the abatement due to the substitution of these non-legume crops by legumes is reduced), the overall abatement becomes 28 Tg CO_2e (calculation not shown). This slight reduction is due to the relative independence of most sub-measures covering a wide range of agricultural practices. This cumulated abatement cannot be directly compared to annual emissions from the agricultural sector in France as they are currently estimated using 1996 IPCC recommendations that differ from our calculation. Interestingly, the cumulated abatement of the 26 sub-measures calculated under current inventory rules was only 10 Tg CO_2e y^{-1}, which is about 10% of the emissions from the agricultural sector (105 Tg CO_2e in 2010). This discrepancy is due to the fact that the expected abatement of several mitigation practices such as reduced tillage or modified animal diets cannot be accounted for by current inventory calculations, which are based on default values.

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

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

A further third of the expected overall abatement potential is linked to sub-measures with moderate cost (less than 25 euros per metric Mg of avoided CO_2e). This category includes sub-measures which require specific investments (e.g. methanisation 9A) and/or associated with a slightly bigger modification of the cropping system (reduced tillage 3, agroforestry 5A, increase in legume crops 2A) which may result in modest reductions in yields (e.g. -2.1% with occasional tillage[1]), partly compensated for by a reduction in costs (fuels) or sales of

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[1] This figure was derived from statistics provided by the French Ministry of Agriculture comparing yields under conventional and reduced tillage.

other products (electricity, wood).

The final third of the overall abatement potential is linked to sub-measures with higher cost (more than 25 euros per metric Mg of avoided CO_2e). This category includes sub- measures requiring investment with no direct financial return (e.g. flares 9B), the purchase of particular inputs (e.g. nitrification inhibitor 1D, unsaturated fats or additives incorporated in the diet of ruminants 7A and 7B), dedicated labour time (e.g. cover crops 4A, hedges 5B) and/or involving bigger reductions in yields (e.g. grass buffer strips which reduce the cultivated surface area 4C), with little or no reduction in costs and no additional product for sale.

3.2 Effect of calculation assumptions on estimated abatements and costs

3.2.1 Effect of induced emissions on calculated abatements

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

3.2.2 Effect of subsidies on calculated costs

Table 4 shows the calculated costs including and excluding state subsidies for the three sub-measures mainly concerned. The subsidies considered here are only those that cannot be separated from current prices (such as subsidies when the electricity produced by methanisation is purchased and tax exemption for agricultural fuels). "Optional" subsidies, such as single payment entitlement (SPE), coupled aids and regional subsidies, were excluded from the cost calculations. For the majority of the sub-measures, subsidy inclusion does not or only slightly modifies the calculation of cost per metric Mg of avoided CO_2e (data not shown). However, there is a bigger difference for the methanisation sub-measure, due to the subsidised purchase of the electricity produced. The difference is also notable in the sub-measures involving high direct energy consumption, given the implicit subsidy represented by the tax exemption for agricultural fuel.

4. Discussion

This study confirms that there is a significant abatement potential in the French agricultural sector. Assuming additivity, the overall abatement potential is estimated at 32.3 Tg CO_2e per year in 2030 (28 Tg CO_2e if interactions between sub-measures are considered). This abatement potential was obtained using a conservative approach, mainly based on readily implementable technical measures for which there is a clear scientific consensus, either peer-reviewed or within INRA. The estimate was further reduced by rejecting measures involving major changes in production systems or which reduce yields (e.g. organic farming), still at a research stage (e.g. plant and animal breeding) or with low social acceptability (e.g. transgenesis). It is thus likely to be under-estimated. Additional measures which are still at the research stage are likely to become available in the near future. Moreover, for some of the selected measures whose full adoption is expected to take time, the percentage of the potential applicability reached in 2030 was estimated with caution (e.g. 7% for agroforestry). This suggests that an additional abatement potential exists if incentive policies encourage the adoption of these measures. Except for a few measures, the calculated abatement was not notably modified when emissions produced upstream or downstream of the farm were included. This shows that the selected measures can be implemented without any risk of emission swapping in other sectors or elsewhere in the world. As many barriers are known to hamper the adoption of climate smart agricultural practices (Long et al., 2016), a research effort is now required to identify the most cost-effective incentive policies.

Interestingly, the total abatement was only 10 Tg CO_2e per year when calculated under current inventory rules, which represents 10% of current emissions from the French agricultural sector. This underlines the need to upgrade these inventory rules, so that efforts to reduce emissions can be taken into account.

One third of the total abatement potential was at negative cost thanks to input savings, and another third was at low cost (less than 25 euros per metric Mg of avoided CO_2e). The results of the present study thus confirm that a large proportion of the abatement potential in agriculture can be obtained without reducing the profitability of agricultural activities - in fact, sometimes even increasing it - thanks to the reduction in GHG emissions and savings obtained by input savings enabled by technical adjustments (e.g. more efficient application of fertiliser). The reasons why these “win-win” measures are not readily implemented by farmers are discussed by Moran et al. (2013) and are the focus of ongoing research and policy in several countries.

Among the 26 selected sub-measures, 12 are related to nitrogen management and represent 28% of the total potential abatement. Eight of these 12 sub-measures belong to the “win-win group”. The weighted average cost of N-related sub-measures is -54.5€ per metric Mg CO_2e avoided whereas it is + 5.1€ per metric Mg CO_2e avoided for all sub-measures. The abatement potential of these N related measures increases if emissions induced upstream are included, since the industrial production of nitrogen fertilisers is a highly energy consuming and GHG emitting process. Moreover, better management of the N cycle in agriculture is also expected to have positive effects on water and air quality. This identifies N management as a key lever for multi-agri-environmental purposes, not only reducing GHG emissions but also preserving water and air quality. The other key levers are linked to carbon storage in soils and biomass (30% of the total potential abatement), which also deserve other objectives (soil fertility, reduction of erosion risk), and energy savings and production on farms.

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

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_2e) 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_4 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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Table 1: List of the 10 measures and 26 sub-measures selected to reduce GHG emissions from the agricultural sector in France

	Measures and sub-measures	Targeted gas
Reduce the application of mineral nitrogen fertilisers to reduce associated N_2O emissions		
❶	**Reduce the use of synthetic mineral fertilisers: 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_2O
❷	**Increase the use of legumes: 2A.** Introduce more grain legumes in arable crop rotations **- 2B.** Increase legumes in temporary grassland	N_2O
Store carbon in soil and biomass		
❸	**Develop no-till cropping systems:** Three technical options: continuous direct seeding, direct seeding with occasional tillage, i.e. 1 year out of 5, or continuous surface tillage	CO_2
❹	**Introduce more cover crops, vineyard/orchard cover cropping and grass buffer strips in cropping systems: 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_2 N_2O
❺	**Develop agroforestry and plant hedges: 5A.** Develop agroforestry with a low tree density **- 5B.** Plant hedges around the edges of fields	CO_2
❻	**Optimise grassland management: 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_2 N_2O
Modify animals' diets to reduce enteric CH_4 emissions and N_2O emissions related to manure		
❼	**Replace carbohydrates with unsaturated fats and use an additive in the diet of ruminants: 7A.** Replace carbohydrates by unsaturated fats in the diet**- 7B.** Incorporate an additive (nitrate-based) in the diet	CH_4
❽	**Reduce the amount of protein in the diet of livestock: 8A.** Reduce the nitrogen content in the diet of dairy cows**- 8B.** Reduce the nitrogen content in the diet of pigs	N_2O
Recycle manure to produce energy and reduce fossil fuel consumption to reduce CH_4 and CO_2 emissions		
❾	**Extend methanisation and install flares: 9A.** Extend methanisation **- 9B.** Cover storage tanks and install flares	CH_4
❿	**Reduce consumption of fossil fuel by farm buildings and machinery: 10A.** To heat livestock buildings **- 10B.** To heat greenhouses**- 10C.** Consumed by agricultural machinery	CO_2

Table 2: Unitary abatement (UA, in kgCO$_2$e/unit/year), unitary cost (UC, in €/unit/year) and maximum technical potential applicability (MTPA, in number of units) of sub-measures in 2030. Unitary abatement includes only direct and indirect emissions, and excludes induced emissions (see text).

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
Reduce the application of mineral nitrogen fertilisers		kgCO$_2$e/ha/year	€/ha/year	millions of ha		
❶	A. Adjust fertiliser application rates to realistic yield targets	222	-8.7	11.7	**Modification:** calculate the nitrogen balance using more realistic yield targets **UA:** -19.7 kgN/ha on average **UC:** €-18/ha (less N fertiliser); €+9.3/ha (cost of N management tools); no loss of production **MTPA:** fertilised arable crops (except sugar beet) and silage maize	**Fertiliser application practices:** 2006 "Cropping practices" survey **Surface area:** 2010 Annual farming statistics (SAA) **Prices, yields:** RICA 2010 database
	B. Make better use of organic fertiliser	156	-11.6	12.0	**Modification:** take organic N more effectively into account, reduce losses (volatilisation), increase volumes of recycled waste **UA:** -14.4 kgN/ha **UC:** €-13.1/ha (less N mineral fertiliser); €+1.5 (cost of incorporation); no loss of production **MTPA:** fertilised arable crops (except rice) and silage maize	
	C. Adjust application dates to crop requirements	231	-22.7	1.8	**Modification:** suppress the 1st N application on winter crops **UA:** -15 kgN/ha; -30 kg CO_2/ha (savings in fuel) **UC:** €-13.7/ha (less N mineral fertiliser); €-9/ha (saving in fuels); no loss of production **MTPA:** winter arable crops with high residual N	
	D. Add a nitrification inhibitor	262	15.8	2.3	**Modification:** use nitrification inhibitors (e.g. DMPP) **UA:** -10.2 kgN/ha; -3kg CO_2/ha (savings in fuel due to fewer application dates) **UC:** €+31.2/ha (cost of inhibitor), €-9.3/ha (less N mineral fertiliser); €-6.1/ha (savings in fuels), no loss of production **MTPA:** arable crops (except sunflower, rice), return frequency of 1 year/5	
	E. Incorporate fertiliser in the soil	154	-9.1	3.7	**Modification:** incorporate fertilisers into the soil **UA:** -12.3 kgN/ha **UC:** €-11.2/ha (less N mineral fertiliser); €+2/ha (special equipment for seed drill); no loss of production **MTPA:** spring arable crops, using solid fertiliser at the time of sowing	
❷	A. Introduce more grain legumes in arable crop	1044	19.4	0.88	**Modification:** include a grain legume instead of wheat (1/6), barley (2/3) and oilseed rape (1/6) **UA:** no N fertiliser needed on legume	**Current practices:** 2006 "Cropping Practices" survey

	rotations				crop, -33 kgN/ha on following crop **UC:** savings (N fertiliser, application operations), modification of the gross margin (legume and following crop) **MTPA:** 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 (*Aphanomyces euteiches*)	**Fuel consumption values** : 2010 Centre – Ile-de-France region mutual aid scale **Surface area**: 2010 Annual farming statistics (SAA) **Soil characteristics:** INFOSOL INRA **Prices, yields, gross margins:** RICA 2010 database
	B. Increase legumes in temporary grasslands	171	-31.5	2.82	**Modification:** increase and maintain the proportion of legumes in temporary grassland **UA:** -29 kgN/ha on average **UC:** savings (fertiliser, application operations), yield not affected **MTPA:** all temporary grasslands with less than 40% legumes (no technical restrictions)	
Store carbon in soil and biomass		kgCO$_2$e/ha/year	€/ha/year	millions of ha		
❸	Switch to occasional tillage	389	3	10.1	**Modification:** switch from tillage or tillage every other year to direct seeding with tillage every 5 years **UA:** C storage (-100 kgC/ha/year); savings in fuel (-88 kgCO$_2$/ha/year); higher N$_2$O emissions (+56 kgCO$_2$e/ha/year) **UC:** yield decreases 4 years out of 5 (-2.6%); more herbicides; savings in fuels and labour **MTPA:** arable surface areas (except potatoes, sugar beet, monocropped maize) and except poorly drained soils	**Current practices:** 2006 "Cropping Practices" survey **Surface area:** 2010 Annual farming statistics (SAA) **Soils characteristics:** Corine Land Cover data and INFOSOL INRA **Prices, yields:** RICA 2010 database
❹	A. Extend the use of cover crops in arable cropping systems	252	41	4.3	**Modification:** cover crops composed of legumes (15% of surface areas), cover crops for long fallow periods and promoting previous crop volunteers **UA:** C storage (-240 kgC/ha/year), less N fertiliser (-11 kgN/ha) **UC:** fertiliser savings, more labour, no loss of production **MTPA:** only before spring crops, except soils with a clay content >60%, return frequency of 1 year/6 for legumes	**Current practices:** 2006 "Cropping Practices" survey **Surface area:** 2010 Annual farming statistics (SAA) **Soils characteristics:** Corine Land Cover data
	B. Extend the use of cover crops in vineyards and orchards	718	10	0.2	**Modification:** permanent cover crops (orchards, between every second row in some vineyards), and temporary cover crops (over the winter in some vineyards) **UA:** C storage (orchards: -490 kgC/ha/year, vineyards: -320) **UC:** more labor, no loss of production **MTPA:** 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	**Modification:** plant grass buffer strips along water courses **UA:** C storage (-490 kgC/ha/year when replacing crop; 0 when replacing grassland); no N fertiliser **UC:** No inputs, no marketable product on	

					the green cover surface area **MTPA:** all edges of water courses	
❺	A. Develop agroforestry with a low tree density	3717	49.6	5.9 but only 0.413 (=7%) reached in 2030	**Modification:** low density trees (30-50 trees/ha) within fields (annual crops) or on grassland **UA:** C storage (in soil, underground and above-ground biomass): -1.01 MgC/ha/year **UC:** investment in and maintenance of trees, production losses, but timber can be sold **MTPA:** all arable/grassland surface areas, with soil depth >1 m and water holding capacity >120 mm, fields > 4 ha	**Crop and grassland management:** 2006 "Cropping Practices" survey **Agroforestry management:** European Silvo-arable Agroforestry For Europe (SAFE) research project **Surface area:** 2010 Annual farming statistics (SAA) **Soils characteristics:** INFOSOL INRA **Prices, yields, gross margins:** RICA 2010 database
	B. Plant hedges around the edges of fields	702	75	12.1 but only 1.815 (=15%) reached in 2030	**Modification:** trees around the edges of fields in grassland and cultivated crops **UA:** 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) **UC:** investment in and maintenance of trees, production losses, but wood can be sold **MTPA:** all arable and grassland surface areas, with soil depth >0.5 m, and fields > 4 ha	
❻	A. Extend the grazing period	50	-26	4.0	**Modification:** extend the grazing season by 20 days **UA:** ↘ CH_4 and N_2O from livestock, ↘ fuel consumption **UC:** ↘ in consumptions (manure, feed) **MTPA:** grasslands grazed by dairy cows or mixed dairy/beef herds; excluding farms where maize accounts for <10% of the main forage area	**Fertilisation levels and age of grassland:** 2006 "Cropping Practices" survey **Number of cattle and surface areas of grassland:** 2010 Annual farming statistics (SAA) **Feed ration typology:** Dairy cow diet observatory and French Livestock Institute **Prices, yields:** RICA 2010 database
	B. Increase the lifespan of temporary sown grassland	612	-112	2.35	**Modification:** increase the lifespan of sown grassland to 5 years **UA:** C storage (↘ tillage): -0.14 MgC/ha/year, ↘ N_2O (slower mineralisation), ↘ fuel consumption **UC:** ↘ in soil tillage and sowing **MTPA:** 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	**Modification:** reduce applications of mineral fertiliser **UA:** ↘ fertiliser application (-5% to -25% depending on the current dose) **UC:** fertiliser savings (-€8/ha), no loss of production **MTPA:** grassland receiving mineral fertiliser	
	D. Make not very productive permanent grassland moderately more intensive	940	-4	0.5	**Modification:** ↗ 20% in livestock density (+0.24 LSU/ha) **UA:** C storage (↗ of primary production): -0.39 MgC/ha/year, ↗ CH_4, N_2O from livestock, ↗ fuel consumption **UC:** sale of hay (-€5.3/ha) **MTPA:** low productive grassland located close to other grazing land	
Modify animals' diets		kgCO_2e/animal/y	€/animal/year	millions of animals		
❼	A. Replace carbohydrates by	287	76.7	6.6(1)	**Modification:** +3 to 3.5% of fatty acids in dry matter in the feed ration (4.5 to 5% in total)	**Numbers and categories of cattle:** 2010

	unsaturated fats in diets				**UA:** -14% CH$_4$ (for +3.5% fats) **UC:** replace some of the carbohydrates with fats, no loss of production **MTPA:** animals receiving > 1 kg/day of feed concentrate during the period when they are indoors	Annual farming statistics (SAA) **Feed ration typology:** 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	**Modification:** the modified feed ration contains 1% nitrate **UA:** -10% CH$_4$ (for 1% nitrate) **UC:** purchase of nitrate and urea savings, no loss of production **MTPA:** animals receiving a diet low in fermentable nitrogen when they are indoors	
⑧	A. Reduce the nitrogen content in the diet of dairy cows	124	-11.6	1.96	**Modification:** ↘ crude protein in feed rations (target 14%) **UA:** ↘ N$_2$O emissions from manure (indoors, during storage, on grassland) and manure spreading **UC:** modification of feed ration, ↘ milk production (-0 to 25 liters) and ↘ in protein content (-0.1 to -0.3 g/l) **MTPA:** dairy cows with winter feed rations containing more than 14% crude protein	**Animal numbers:** 2010 Annual farming statistics (SAA) **Feed rations typology:** Dairy cow diet observatory and French Livestock Institute
	B. Reduce the nitrogen content in the diet of pigs and sows	510	-49.2	0.95(2)	**Modification:** synthetic amino acids and cereals in place of oil meals (soybean meal and rapeseed meal) and peas **UA:** ↘ N$_2$O emissions from manure (indoors, during storage, on grassland) and manure spreading **UC:** modification of feed ration, no loss of production **MTPA:** exclusion of boars and unproductive sows	
Recycle manure to produce energy, reduce fossil fuel consumption		kgCO$_2$e/unit/year	€/unit/year	Number of units		
⑨	A. Extend methanisation	473770 kgCO$_2$e/farm/year	8283 €/farm/year	48800 farms but only 12200 (=25%) equipped in 2030	**Modification:** upstream outdoor storage limited to 3 weeks (duration ↘ by 88%), digestion in a reactor with energy production (50 kWe unit) **UA:** ↘ CH$_4$, ↘ N$_2$O for solid manure only (anaerobic conditions) **UC:** investment (€9000/kWe) and operating costs; sale of electricity **MTPA:** farms with > 140 LSU (i.e. 62% of total number of livestock)	**Manure management practices:** Survey of livestock buildings **Number of animals:** 2010 Annual farming statistics (SAA) **Size of farm herd:** RICA 2010 database
	B. Cover storage tanks and install flares	170000 kgCO$_2$e/farm/year	10075 €/farm/year	40000 farms but only 20000 (=50%) equipped in 2030	**Modification:** capture and combustion of CH$_4$, with no production of energy **UA:** ↘ CH$_4$ **UC:** investment (covering and flare) and operating costs (maintenance and monitoring) **MTPA:** applied to liquid manure and only for livestock not concerned by methanisation	
⑩	A. Reduce consumption of fossil fuel for heating livestock buildings	0.28 kgCO$_2$e/animal produced	-0.081 €/animal produced	886 million animals produced per year but only	**Modification:** improve the heating and insulation system **UA:** energy savings (from 15% to 50% depending on the technical options) **UC:** investments and energy savings **MTPA:** all meat poultry buildings	**Current energy consumption:** Inter-trade technical centre for fruit and vegetables; Pig

	(meat poultry)			709 million (=80%) concerned in 2030		Institute; Technical institute for poultry farming **Number of animals:** 2010 Annual farming statistics (SAA) **Numbers and characteristics of tractors:** "Equipment" census (2005, Agreste)
	A. Reduce consumption of fossil fuel for heating greenhouses	3.94 kgCO$_2$e/m^2/year	-0.57 €/m^2/year	20.3 million m^2	**Modification:** improve insulation and install hot water tanks **UA:** energy savings (from 5% to 22% depending on the technical options) **UC:** investments and energy savings **MTPA:** all greenhouses (25,4 million m^2) except those already equipped	
	C. Reduce consumption of fossil fuel by agricultural machinery	2554 kgCO$_2$e/tractor/year	-410 €/tractor/year	0.84 million tractors but only 0.64 million (=75%) concerned in 2030	**Modification:** eco-driving and adjustments after bench test **UA:** ↘ diesel consumption: bench test (-10%) and eco-driving (-20%) **UC:** costs (bench test, training for eco-driving) and energy savings **MTPA:** all tractors used (eco-driving), only recent tractors (1/3 of fleet) (test bench)	

(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)

Table 3: Main sources of data

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 Livestock numbers	Annual statistics of agriculture (Agreste, SAA - 2010)
	Yields	French Farm Accountancy Data Network (Agreste, RICA - 2010)
	Land characteristics and use	Geographic database for land use in France on a scale of 1/1 000 000 (BDGSF) European land cover map (Corine Land Cover)

Table 4: Calculated costs including or excluding state subsidies for three sub-measures

	Cost of the sub-measure (€ per metric Mg of CO_2e 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

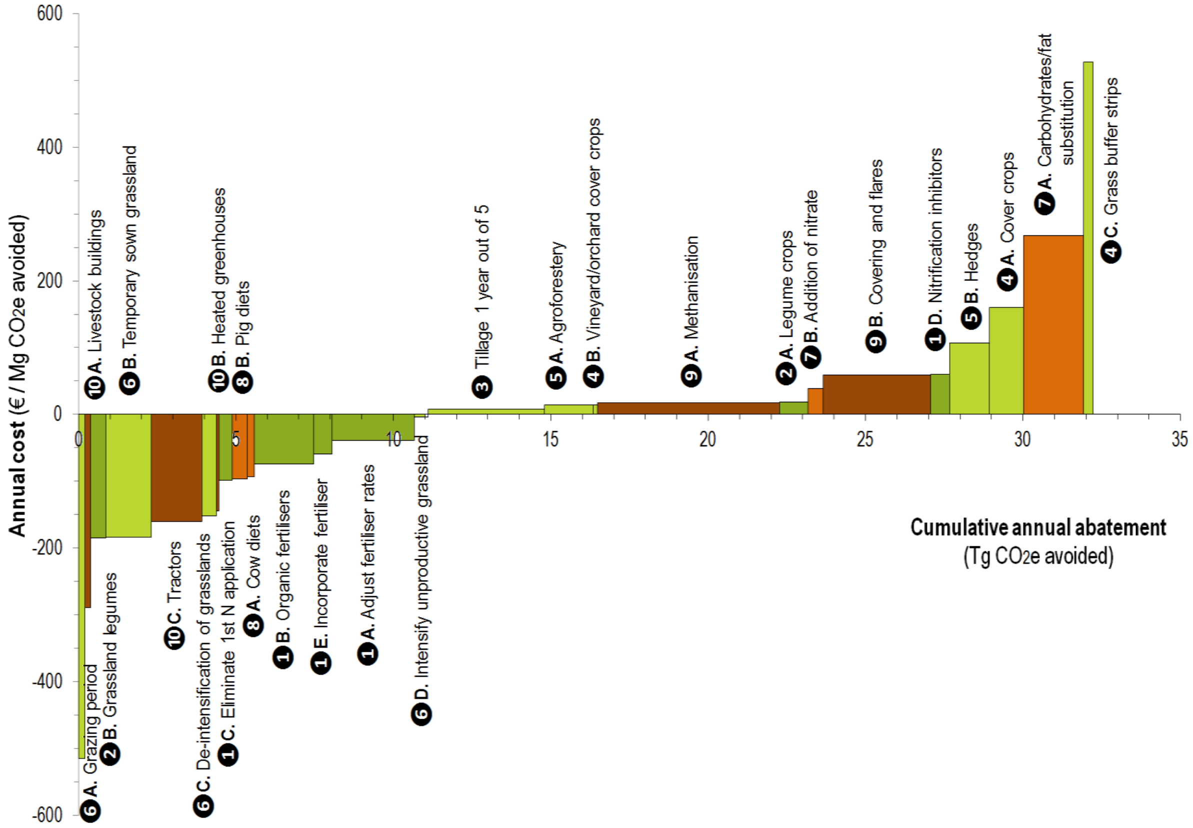

Figure 1: Cost (in € per metric Mg of CO_2e avoided) and annual abatement potential in 2030 at the scale of mainland France (in Tg CO_2e avoided per year) of the 26 sub-measures. The annual abatement was calculated not including induced emissions (see text). For measure 3 (develop no-till cropping systems) 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.

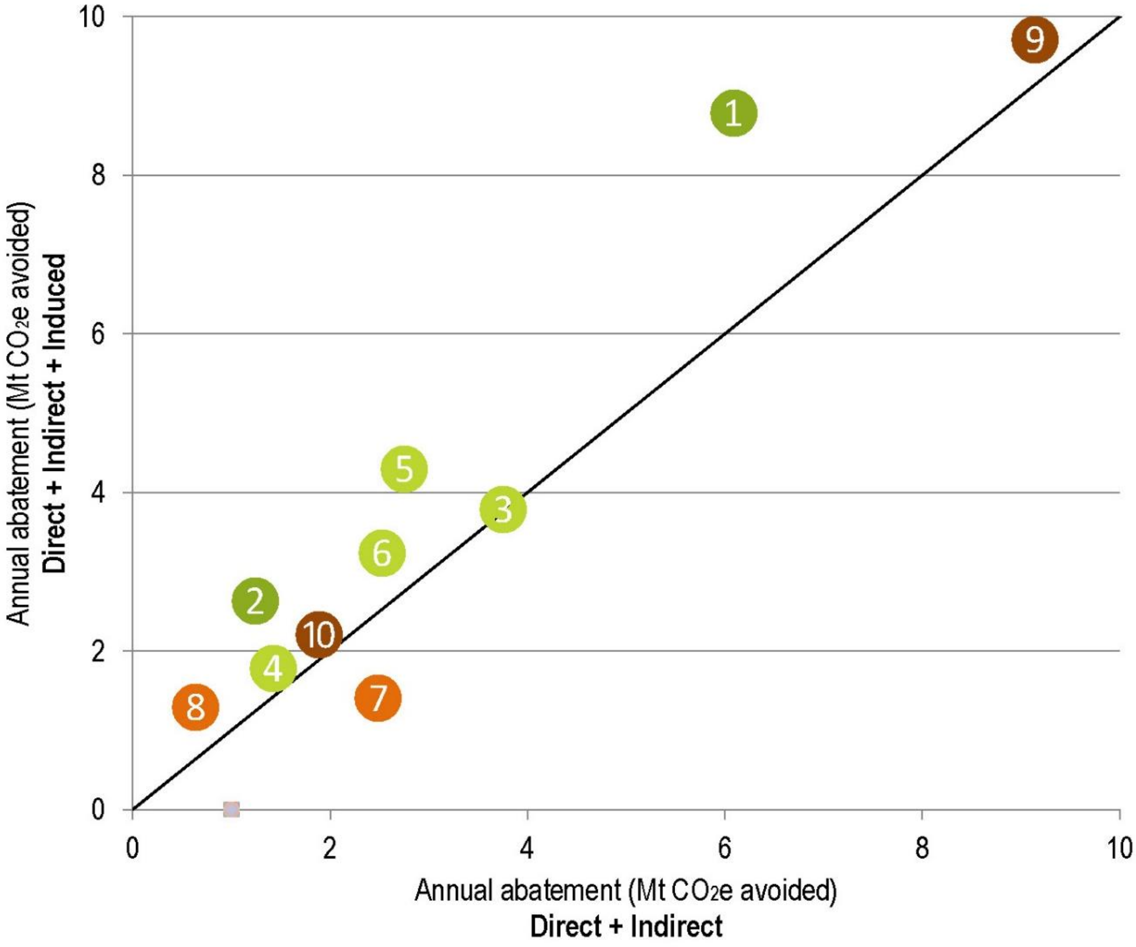

Figure 2: Total annual abatement per measure, including induced emissions, as a function of the abatement excluding induced emissions (in Tg CO_2e per year, calculation for the year 2030). The number of each measure is given (for explanation, see Table 1).

Supplementary material: Measures not selected and why

Levers and measures	*Reason it was not selected*
Modify the physicochemical conditions of soils to discourage CH_4 and N_2O-producing reactions	
Optimise the physical-chemical soil conditions to limit N_2O emissions (for example, optimise pH by liming).	*The abatement potential is uncertain. N_2O 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_2O 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.*
Modify the microbial communities of soils by incorporating microorganisms that reduce N_2O into N_2 (incorporation of Rhizobia strains living in symbiosis with legumes, for example).	*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).*
Promote aeration of rice-growing soil to reduce fermentation reactions and limit CH_4 emissions (reduce the depth of paddy	*Potential applicability is limited in France with only around 20,000 ha of paddy fields.*

fields, empty them several times a year, for example).	
Reduce application of nitrogen fertiliser on crops to reduce N_2O emissions	
Genetically improve the nitrogen uptake and nitrogen use efficiency of crops to enable a reduction in nitrogen fertiliser application.	*Not applicable in the short term. Long term breeding programs are required before this measure will be efficient.*
Reduce CO_2 losses to the atmosphere by reducing flows from biomass and soils	
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).	*The abatement potential is low since burning crop residues is rare in France where most crop residues are already returned to the soil.*
Avoid cultivating wet zones to limit the release of CO_2 stored in organic matter.	*Potential applicability is limited in France because there are few cultivated zones that could be returned to wet zones.*
Increase CO_2 inputs through increased biomass production, thereby increasing flows from the atmosphere towards biomass and soils	
Increase the production of biomass by optimising production factors in order to increase the return of carbon to the soil.	*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.*
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).	*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.*
Restore degraded soil to increase organic matter production and store carbon in soil (acidified, eroded, saline soils).	*Potential applicability is limited in France.*
Spread "inert" carbon (biochars, plant charcoal) on cultivated land to store carbon.	*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)*
Increase livestock productivity to reduce per head CH_4 and N_2O emissions	
Select livestock on the basis of growth rate, milk production or prolificacy traits.	*Animal breeding for productivity is a long term process that is already underway.*
Select cattle on the basis of residual feed consumption criteria (efficiency of nutrient use) or directly on the basis of CH_4 emissions.	*Breeding animals to match these new criteria is a long term project (Eckard et al., 2010). Moreover, the heritability of enteric CH_4 emission and its genetic correlation with other traits were not known when the present study started (Basarab et al., 2013).*
Improve herd management and health to increase livestock productivity.	*The abatement potential is low given that this approach to herd management is already implemented in France.*
Use products that increase per head production (meat or milk).	*The use of bovine somatotropin, the only additive proven to be effective on milk production, is banned in the European Union.*
Develop mixed breeds or industrial cross-breeding in cattle to reduce per head GHG emissions.	*This measure would significantly modify livestock farming systems and its abatement potential per kg of milk or meat is uncertain.*
Alter rumen function to reduce enteric CH_4 emissions	
Regulate populations of microorganisms promoting the production of methane in the rumen using antibiotics.	*The use of antibiotics for non-curative purposes is banned in the European Union.*

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).	*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).*
Modify feed to reduce CH_4 and N_2O emissions	
Modify the nutritional characteristics of forage, favoring non-methanogenic substances (increase the tannin or saponin content of forage for instance).	*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)*
Increase the percentage of feed concentrate in the diet.	*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).*
Optimise manure management	
Reduce the amount of livestock manure stored in order to reduce CH_4 emissions due to manure fermentation	*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)*
Optimise the type of manure produced to obtain a CH_4/N_2O balance minimising the global warming potential per unit of manure (favour solid manure rather than slurry, composting, etc.).	*The global abatement potential is uncertain, because* CH_4 *and* N_2O *are produced during the whole management process and emissions are controlled by many factors (Chadwick et al., 2011).*
Optimise manure management and storage to reduce N_2O and CH_4 emissions	*Measure initially selected but subsequently abandoned due to the technical difficulties involved in examining it*
Produce energy from biomass or livestock manure	
Produce dihydrogen from livestock manure using an anaerobic process and convert it into energy.	*Still at the research stage. Technical obstacles need to be overcome, particularly the chronic instability of the processes*
Produce energy on the farm by biomass combustion	*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)*
Reduce fossil energy consumption on farm	
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).	*A significant proportion of the expected abatement is located outside the farm (lower energy consumption by collect organisations)*