How can French agriculture contribute to reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures

Sylvain Pellerin, Laure Bamière, Denis Angers, Fabrice Béline, Marc Benoit, Jean-Pierre Butault, Claire Chenu, Caroline Colnenne-David, Stéphane de Cara, Nathalie Delame, et al.

HOW CAN FRENCH AGRICULTURE CONTRIBUTE TO REDUCING GREENHOUSE GAS EMISSIONS?

ABATEMENT POTENTIAL AND COST OF TEN TECHNICAL MEASURES

Summary of the study report conducted by INRA
on behalf of ADEME, MAAF and MEDDE – July 2013

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Delegation for Scientific Expertise,
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How can French agriculture contribute to reducing greenhouse gas emissions?

Abatement potential and cost of ten technical measures

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July 2013

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Foreword

Now recognised as one of the major factors influencing climate change on our planet, controlling net greenhouse gas (GHG, mainly CO_2, N_2O and CH_4[2]) emissions is a major objective. Limiting emissions from the agricultural sector is difficult, but will become increasingly essential as other GHG-emitting economic sectors gradually manage to reduce their emissions. Conversely, agriculture could make a significant contribution to increasing carbon storage in soil and plant biomass

If global reduction targets are achieved in 2050 without any reduction in agricultural emissions, the proportion of the latter in total emissions will increase from 24%[3] to over 75% of total levels, whereas agriculture only accounts for a few percent of global GDP. It should be noted that, on a world scale, the increase in population and change in dietary habits is likely to simultaneously lead to an increase in food availability of approximately 70% (FAO 2009). Hence, it is necessary to reduce emissions while at the same time continuing to significantly increase agricultural production.

Like several other OECD countries, France has launched an ambitious policy aimed at reducing its emissions: Europe has committed to reducing its emissions by 20% by 2020 compared to levels in 1990, the reference year, while France aims to achieve a 75% reduction by 2050. This drive therefore needs to be reflected in the country's various economic sectors, including the agricultural sector.

Nationally, agriculture accounts for around 2% of GDP and around 20% (including energy emissions) of total GHG emissions (CITEPA 2012).

But emissions in the agricultural sector are diffuse, in contrast with those in numerous other sectors. N_2O, for example, is emitted on almost all cultivated land and all ruminants emit CH_4 linked to the digestion of their food. Furthermore, agricultural emissions are not fully known and are prone to significant variations from one site to another or from one farming system to another. Finally, the large number of farms, along with their significant diversity, across the country, complicates both estimation of these emissions and the mechanism that the public authorities could implement to encourage their reduction.

A number of countries, such as the USA, Canada, Ireland and the United Kingdom, have examined measures that could be implemented to limit the GHG emissions of their agricultural sector. These initiatives are supported by scientific studies aimed at gaining a clearer understanding of emission mechanisms and exploring methods that might limit them. They represent very useful references for the French situation. However, they do not reflect the national reality for emissions in France and they do not enable accurate quantification of the reductions hoped for or the cost of the measures leading to these reductions.

It is against this background that ADEME (French Agency for the Environment and Energy Control), MAAF (Ministry of Agriculture, Food and Forestry) and MEDDE (Ministry of Ecology, Sustainable Development and Energy) commissioned INRA (French National Institute for Agricultural Research) to conduct a study on the abatement of greenhouse gas (GHG) emissions in the agricultural sector in mainland France. The ultimate objective of the study is to draw up an objective inventory of knowledge - one that is as exhaustive as possible - concerning the measures that could potentially be rolled out to limit GHG emissions in agriculture, then to select - using transparent and explicit criteria - ten measures for which the cost/efficacy ratio will be examined in detail. In their commissioning letter, the sponsoring bodies specify that the task requested is to determine and analyse ten abatement measures concerning agricultural practices. The analysis consists in estimating the abatement potential of each of these measures, together with their associated costs or benefits in economic terms.

It is hoped that the results of the study will serve as a basis for the development of public policy aimed at reducing GHG emissions. However, the commission does not include the identification of the policy instruments to be implemented to promote the adoption of the measures examined.

This document constitutes a synopsis of the main stages and the main results of the study, aimed at decision-makers and stakeholders: agricultural practitioners (farmers and advisers) and those managing issues related to the effects of agriculture on the climate. This synopsis is designed to be a key providing access to the various chapters of the study report, for which it follows the plan.

The document first (Part I) sums up the context, the study organisation and the methodology used to select the ten measures to be examined; it then presents (Part II) summary data sheets of the 10 measures examined by the experts, which are described at length in the report; and, finally (Part III), it presents a comparative analysis of the 10 measures. The interim results and/or analyses explaining the main results presented here, along with other additional results, are detailed in the study report.

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[2] Carbon dioxide, nitrous oxide and methane, respectively

[3] 13% from agricultural production itself and 11% from land-use change

Part I

Context and method

1. GHG emissions from the agricultural sector and their incorporation in "climate" protocols

1.1. The context and the issues

Since the start of the industrial age (1870), the temperature of the Earth's surface has increased by 0.8 ±0.2°C, with the trend tending to accelerate in recent years. This global warming is attributed to an increase in net emissions of greenhouse gases (GHG) (primarily carbon dioxide, CO_2; nitrous oxide, N_2O; methane, CH_4) into the atmosphere as a result of human activities (use of fossil fuels, land clearing, agriculture, etc.). Given the expected increase in the world's population and related economic development, it is likely that GHG emissions will continue to increase in the coming decades, leading to an estimated rise in temperatures of between +1.8 and +4°C by the end of the 21st century compared to the 1980-1999 period, according to emissions scenarios. This warming will also lead to general changes in climate (extreme events will become more frequent) ecosystems (species will become extinct) and human activities (agricultural yields, etc.), with variable effects in different regions of the world. However, the intensity of these changes and the capacity of ecosystems and human societies to adapt to them will greatly depend on the extent of global warming and hence the degree of GHG emissions control in the coming decades.

• International, European and French commitments

To address this challenge, governments signed the United Nations' framework convention on climate change at the Rio de Janeiro summit in 1992. A number of international meetings have been held since (in particular, Kyoto in 1997, Bali in 2007, Copenhagen in 2009, Cancun in 2010, Durban in 2011). The Kyoto protocol scheduled an average reduction in GHG emissions of 5.2% in 2008-2012 compared to 1990, for 38 industrialised countries, with the targets varying depending on the region of the world (-8% for the European Union, stabilisation for France). Despite significant difficulties, "post-Kyoto" negotiations are ongoing, the aim being to develop a new international climate agreement for the coming period.

For its part, the European Union is committed to cutting its emissions by 20% by 2020 compared to the reference year of 1990 (i.e. a 14% fall compared to 2005 levels). If a satisfactory international agreement can be reached, it may consider an even more ambitious target (-30% instead of -20%). The target of a 20% reduction in GHG emissions has been incorporated in the "20-20-20" commitment of the EU's Energy and Climate package (a 20% improvement in energy efficiency, an increase in the share of renewable energies to 20%, a 20% reduction in GHG emissions). For emissions categories not covered by the EU's emission trading system[4], such as those related to transport, construction and agriculture, the overall reduction target assigned to France is -14% by 2020 compared to 2005. Reaching these targets assumes the active commitment of all the emitting sectors concerned, including the agricultural sector. In the longer term, the European target for reducing emissions is -80% by 2050 compared to 1990 levels, with intermediate steps (-25% by 2020, -40% by 2030, -60% by 2040). In France, ambitious targets were included in the energy policy bill of 13 July 2005, and confirmed in the law of 3 August 2009 relating to the implementation of the French Environment Round Table (*Grenelle de l'environnement*) ("factor 4": cutting emissions by a factor of four by 2050 compared to 1990).

The level and evolution of GHG emissions are recorded in national inventories, produced using international nomenclatures and measurement rules developed by the IPCC (Intergovernmental Panel on Climate Change), and periodically updated to incorporate advances in scientific knowledge. In France, this inventory is drawn up by the CITEPA (*Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique - Interprofessional Technical Centre for Studies on Air Pollution).*

• Agricultural emissions

Worldwide, agriculture accounts for 13.5% of emissions (30.9% if land-use changes, including deforestation, are added) (IPCC, 2007). In France, agriculture accounts for 2% of the gross domestic product, but 17.8% of emissions (excluding energy consumption and land-use change) estimated by the national inventory, with 94 Mt of CO_2 equivalent (CO_2e) out of a total of 528 MtCO_2e (2010 Inventory of emissions, CITEPA 2012).

A specific feature of agricultural emissions is that they are mostly non energy-related and controlled by biological processes. Of the 17.8% of emissions produced by agriculture, 9.8% are due to nitrous oxide (N_2O), produced during biochemical nitrification and denitrification reactions, while 8.0% are related to methane (CH_4), produced during anaerobic fermentation (Figure 1). Agriculture is thus responsible for 86.6% of French N_2O emissions excluding LULUCF (Land use, land-use change and forestry): 35% are related to direct emissions[5] by agricultural land, 28% to indirect emissions, 15% to livestock production and manure management and 8.6% to manure management. Likewise, agriculture is responsible for 68% of French CH_4 emissions excluding LULUCF: 46% are a result of enteric fermentation and 22% are related to manure management.

The 17.8% of emissions attributed to agriculture do not include emissions related to its energy consumption, which are counted in the "Energy" sector of the national inventory. If these emissions are incorporated (Table 1), the share of agriculture rises to around 20% of total French GHG emissions, with N_2O, CH_4 and CO_2 respectively accounting for 50%, 40% and 10% of the sector's emissions, expressed in CO_2e. The weight of N_2O and CH_4 emissions in the inventory is related to their 100-year global warming potentials (GWP), which are much higher than that of CO_2 (GWP_{CO2} = 1, GWP_{CH4} = 25, GWP_{N2O} = 298; new values proposed by the IPCC since 2006); for equal amounts released into the atmosphere, CH_4 will thus have a 25 times greater impact on global warming than CO_2.

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[4] CO_2 emissions allowances mechanism implemented within the European Union. Each company has a certain quota of CO_2 emissions allowances and can buy or sell allowances.

[5] Direct emissions are produced on the farm, compared to indirect emissions produced on physically linked natural areas (leaching of nitrate carried by water, which percolates into soil, and volatilisation of nitrogen in the form of ammonia; then denitrification outside the farm).

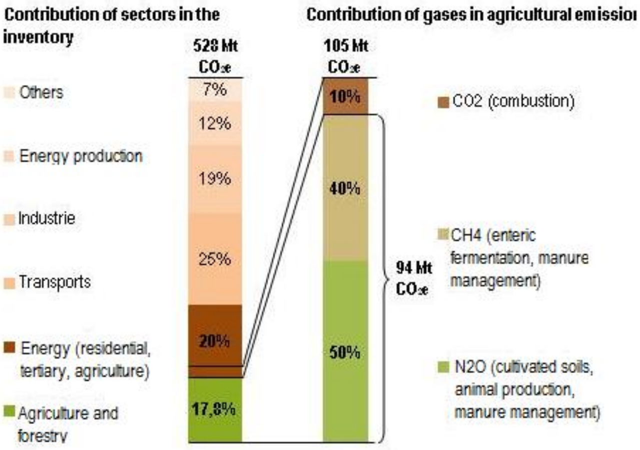

Figure 1. GHG emissions in 2010, mainland France and Overseas territories (Source: CITEPA 2012)

Given its contribution to national emissions, agriculture is required to play its part in the general drive to reduce GHG emissions and achieve the national and international targets set. Agriculture can help improve the net GHG emissions balance via three levers: a reduction in N_2O and CH_4 emissions, carbon storage in soil and biomass, and energy production from biomass (biofuels, biogas), reducing emissions by replacing fossil energies. The majority of authors agree that there is considerable scope for progress but, given the predominantly diffuse nature of the emissions and the complexity of the underlying processes, estimating emissions is riddled with uncertainty and the abatement potentials are currently less accurately quantified than in other sectors. Exploration and quantification of the possibilities for emissions abatement in the agricultural sector is therefore necessary but difficult. In addition, agriculture lies at the centre of numerous converging issues (food safety, employment and rural development, biodiversity and landscape, water and air quality, etc.) and, as in other sectors, the GHG emissions reduction target cannot be examined independently of the other major sectors assigned or related to this sector.

Inventory categories	GHG	Activity variables	Emissions (in CO_2e*)
1.A.4.c Agriculture, forestry, fisheries	CO_2, N_2O, CH_4	Energy consumed in the sector in various forms (liquid, solid, gas, biomass)	10.88 Mt CO_2e
4.A Enteric fermentation	CH_4	Livestock numbers (dairy cattle, beef cattle, sheep, goats, pigs, horses, donkeys)	28.60 Mt CO_2e
4.B Emissions related to the management and storage of livestock manure	CH_4 N_2O	Livestock numbers (dairy cattle, beef cattle, sheep, goats, pigs, horses, donkeys) Amounts of nitrogen contained in manure by type of manure management (slurry, solid manure)	18.87 Mt CO_2e
4.C Rice-growing	CH_4	Rice surface areas	0.11 Mt CO_2e
4.D Agricultural land	N_2O	Nitrogen application to agricultural land in various forms (synthetic nitrogen fertiliser, livestock manure, crop residues, legumes, water treatment plant sludge)	46.74 Mt CO_2e
4.F Burning of agricultural residues in the field	CO_2, N_2O, CH_4	Quantities of residues burned	0.03 Mt CO_2e
5 LULUCF (conversion of grassland into crops or of agricultural land into other uses, and vice versa)	CO_2, N_2O, CH_4	Surface areas concerned by land-use changes	8.91 Mt CO_2e

* 1995 GWP (still used by the CITEPA in 2010): $GWP_{CO2} = 1$, $GWP_{CH4} = 21$, $GWP_{N2O} = 310$

Emissions are expressed in metric tons in this document.
1 Mt (megaton) = 10^6 t (tons); in international units 1 t = 1 Mg (megagram)

Table 1. France 2010: GHG emissions of the agricultural sector, including energy consumption (CITEPA 2012) (National inventory drawn up in accordance with the rules defined by the IPCC in 1996)

1.2. Quantifying emissions

• Quantifying the effects of the measures

GHG emissions estimation methods

Inventory nomenclatures, procedures and rules for the calculation of emissions are jointly defined on an international level by the IPCC. These methods evolve constantly: new "guidelines" were published in 2006, for example, applicable from 2013 in France. The 2010 national emissions inventory (published in 2012) was conducted with the rules defined in 1996.

For each type of GHG emission, the IPCC methodology proposes three calculation levels, of increasing complexity: tier 1 corresponds to the default method (use of easily accessible national or international statistics in combination with default emission factors – for definition of the emission factor, see section 4.2); tier 2 corresponds to regionalised emission factors (derived from scientific studies, with no modification of the equations proposed in tier 1); tier 3 corresponds to different equations or estimation methods (use of modelling possible).

Incorporation of abatement measures

The choices made for the national inventory (tier level selected) determine whether or not the GHG emissions abatement measures considered can be incorporated. For example, France's current choice not to count carbon storage in soil means that some measures cannot be taken into account, which affects the emissions calculated for France and used as a reference in this study.

In the context of international commitments, countries need to develop measures that can be counted in their inventories immediately and hence modify the quantification rules, making use of advances in knowledge.

In order for a measure to have an effect on the inventory and lead to a claimed reduction in GHG emissions, the following conditions must be met:
- the efficacy of the measure must be demonstrated and recognised,
- it must be possible to take into account its effect in the calculation method used in the national inventory,
- it must be possible to prove and check its implementation (control is possible for agroforestry, for example, visible on satellite images, but may be more difficult for a tillage practice, for example).

• National evaluations of agricultural GHG emissions abatement measures

In a context in which countries are striving to attain increasingly restrictive GHG emissions abatement targets, all economic sectors need to contribute to the national objective. Although agriculture has generally been excluded from numerous formal agreements, the emissions reduction potential in this sector is now being closely examined by public decision-makers. To advance the development of rational national abatement policies in this sector, a number of countries have carried out technical and socio-economic studies tailored to the specific characteristics of their climatic and agricultural conditions. More and more literature relating to these issues is becoming available, with, in particular, recent studies having been conducted in Ireland, the UK and the USA.

Some of the questions raised are common to a number of these studies:

- What is the technical potential for the reduction of emissions in the agricultural sector? Which levers are available in terms of land management, crop production and livestock production? Within these levers, the abatement potential for different measures needs to be estimated, taking into account, firstly, the unitary abatement potential (metric ton of CO_2e avoided per ha, per animal, etc.), and, secondly, the potential applicability (surface area, livestock population, etc.) to which the measure can be applied, with combination of the two criteria enabling assessment of the abatement potential on a national scale;
- What is the estimated cost (or benefit) of implementing these measures; which are the least costly and how are these positioned relative to existing abatement measures in other sectors? The estimated cost may be the cost, or saving, of implementing a measure to the farmer, or to the State, if the development of the measure needs to be supported. The efficiency can be expressed in euros per metric ton of CO_2e avoided, enabling comparison of the various measures. Calculation of the cost of the measures is not systematically tackled in the international studies;
- Which measures can be encouraged within the framework of a realistic policy, the aim being for farmers to implement these measures? Various types of measures can be envisaged (regulations, taxes, subsidies, etc.) depending on the nature of the measure (potential cost/saving, ability to verify the measure, etc.).

It is within this political, economic and scientific context that INRA was asked to conduct this study. The objective was to select and analyse ten abatement measures. Compared to comparable studies conducted in other countries, this study presents a few specific characteristics: a measure selection process conducted in several stages and based on a variety of different criteria; an estimation of the costs/savings to farmers; a particular focus on the determination of the potential applicability and technical constraints limiting this, of an adoption scenario and of the technical and socio-economic obstacles that may hamper it.

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2. The study INRA was tasked with: mechanism, scope, method

2.1. The contractor and the project manager

The methodological framework of the study was defined by INRA's Delegation of Scientific Expertise, Foresight and Advanced Studies (DEPE); in particular, it is based on a clear distinction between the functions of contractor and project manager, and on the independence and responsibility of the college of scientific experts tasked with undertaking the study.

• The commissioning bodies: ADEME and the French Ministries for Agriculture and the Environment

The study contractors having formulated the request and helped fund it are:

- the **French Agency for the Environment and Energy Control (ADEME)**, which helps implement public policy in the field of the environment, energy and sustainable development; tackling climate change is one of its fields of focus;

- the **French Ministry of Agriculture, Food and Forestry (MAAF)**, which, within the scope of international negotiations and commitments relating to the climate (which it is responsible for monitoring on behalf of the French Ministry of Ecology, Sustainable Development and Energy (MEDDE)), and application of the new CAP, is seeking scientific results relative to the abatement potential of the agricultural sector;

- the **French Ministry of Ecology, Sustainable Development and Energy (MEDDE)**, which designs and implements climate and energy policy, one of the objectives being to reduce GHG emissions; this policy is associated with other measures in the field of environmental protection (water, biodiversity, etc.).

A **monitoring committee** made up of commissioning body representatives – and which included INRA due to its interest in the spin-offs of the study in terms of research – served as a liaison between the contractors and the project coordinators: more precise definition of the scope of the question asked, monitoring of the study's progress and the consistency between the specifications and the work carried out (oral presentations of the study phases followed by written documents).

A **technical committee** made up of around fifteen field experts (from ADEME, technical institutes, etc.), was also formed. It was consulted regarding the choice of measures proposed by the scientific expert group and asked to supply data from the grey literature, discuss the technical relevance and feasibility of the measures and review documents. A list of monitoring committee and technical committee members is provided at the end of the document.

Finally, the commissioning bodies formed **a stakeholders group** made up of representatives from organisations with an interest in agricultural GHG emissions: professional farming bodies, economic stakeholders (cooperatives, etc.), associations and NGOs. In this way, the stakeholders were informed about the existence of the study.

• Project manager: INRA's Delegation of Scientific Expertise, Foresight and Advanced Studies (DEPE)

Principles and methods of studies designed to support public decision-making

The studies conducted by INRA form part of its public policy-making support mission, alongside the collective scientific expertise and foresight exercises also carried out by the DEPE. Expert assessments and studies are carried out under the responsibility of INRA, at the request of public decision-makers - generally Ministries - by **a multidisciplinary group of scientific experts**. The objective of these two exercises is to draw up **an inventory of current scientific knowledge** that is relevant to inform public action, but they do not include opinions or recommendations. They are conducted in accordance with the principles laid down in INRA's corporate scientific expertise charter.

The expert group formed for each expert assessment or study is tasked with analysing the international scientific literature, extracting and collating the relevant data in order to shed light on the questions asked, and indicating the current situation in terms of knowledge acquired, uncertainties, shortcomings and controversies. The knowledge used is primarily that obtained from the scientific literature (articles published in peer-reviewed journals). Studies in English and French from all geographic regions are examined, provided they are relevant to the French soil, climate and agricultural conditions. The technical literature is included insofar as the sources on which it is based are specified (published experimental data, conditions for obtaining the data clearly defined, etc.).

The "studies" draw on existing knowledge but generally tackle issues for which the academic literature alone is insufficient, requiring that the analytical tools employed be extended to include additional *ad hoc* studies. A study therefore includes a scientific literature analysis component, combined, depending on the cases, with an original data processing approach, broader analysis of the technical literature, or biotechnical and economic simulations. In this study, the objective of quantifying GHG emissions and costs required the performance of numerous calculations.

The DEPE guarantees the method, compliance with the charter, the principles and procedures of the exercise, along with the commitments made (delivery times, etc.). It provides support to the expert group to help it carry out the project and produce documents. This support is provided by a **project team** made up of specialists and support staff from the DEPE, who help coordinate the work (scheduling and organisation of meetings), collate the body of literature (document engineering) and disseminate the results (editorial support for the report, drafting of summary documents, organisation of the seminar for presentation of the study). They also handle logistics and budget monitoring.

• The scientific expert group

The scientific expert group is made up of researchers from public research and higher education institutions; they are selected on the basis of their expertise, as reflected in their academic publications in scientific journals. These experts are jointly responsible for the content of the study, for which they sign the report and the present summary document.

For this study, the group consisted of 22 researchers from INRA and other French and foreign institutions, covering a broad range of scientific disciplines; two of them (an agronomist and an economist), tasked with leading the group, took on the role of scientific coordinators for the purposes of the study. A list of the experts is given at the end of the document.

A few other researchers also made occasional contributions to the study. Finally, scientific reviewers - researchers not involved in the conduct of the study - were tasked with completing a critical review of sections of the study report.

The project consisted of alternating phases of joint work (selection of measures, determination of the methodology used, comparative analysis of the results) and work in small groups for each measure (analysis of the literature, implementation of the calculations).

For each of the 10 measures studied, a "responsible" agronomist or animal scientist and a small group of experts, including an economist, carried out the analytical work; coordination by the scientific managers and the project team ensured the homogeneity of the methods (calculation rules, data sources, etc.) and overall coherence.

Each of the responsible experts conducted an analysis of the international scientific literature and technical applications, applied this inventory of knowledge to a quantitative assessment of the measure (performance of abatement calculations) and integrated the cost estimates made by the economist.

Study team interaction mechanisms

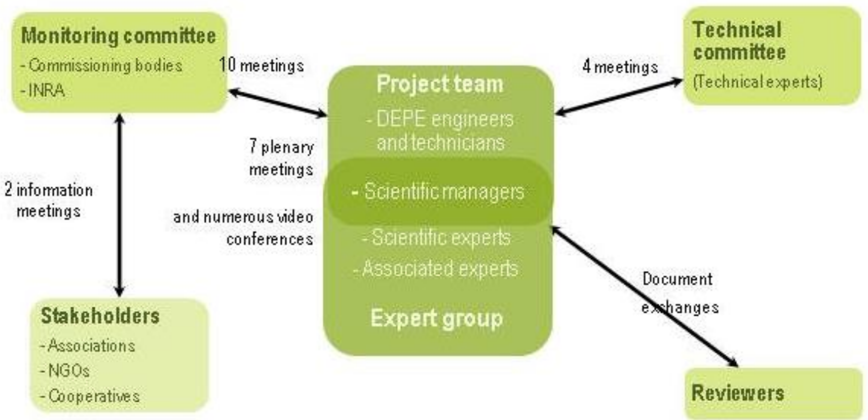


Figure 2

Throughout the study process, interactions were organised between the parties involved. The participation of the two scientific coordinators and the DEPE project team in the monitoring committee meetings (with the commissioning bodies) and technical committee meetings, as well as in the two sessions with stakeholders, ensured an interface between the scientific expert group and the bodies consulted. This interaction method reconciles protection of the scientific expert group's independence and exchange with the stakeholders consulted regarding the project and the studies under way.

2.2. The study process

The study was conducted in four phases, from July 2011 to July 2013: a preliminary project phase corresponding to the initial discussions between the commissioning bodies and INRA and a commissioning letter defining the question asked; a launch phase, with the formation of the scientific expert group and a technical committee, and the drawing up of the study specifications; a scientific study implementation phase (selection and analysis of the measures, followed by comparative analysis) and a phase for synopsis of results, production of documents and preparation of the presentation symposium.

• Definition of the study objectives and scope

It was agreed with the commissioning bodies that eligible measures within the context of this study should meet the following criteria:
- concern an **agricultural practice**, as decided by the farmer;
- be aimed primarily at abating emissions produced on the farm, although, once the measure has been selected, any potential modifications in emissions upstream or downstream of the farm are also quantified.

The scope of the study is agriculture in mainland France. Forestry and dedicated energy crops used outside the farm are excluded from the scope of the study since these have already been the focus of specific studies. The time horizon set for calculation of the abatement potential is 2030.

The measures analysed must:
- be able to be the subject of subsequent public policies or economic incentives, but identification of the incentive mechanisms to be implemented is not one of the expected outcomes of the study;
- concern a diversity of agricultural production focuses;
- be able to be implemented without any major modifications to production systems or locations and without any major reduction in production volumes. Since some measures may potentially lead to a reduction in production output, however, a maximum threshold of 10% was set. Systemic measures affecting the nature of French agricultural production systems and their geographic distribution are therefore outside the scope of the study.

Measures relating to the dietary habits of consumers (for example, the amount of animal products consumed) that may significantly modify the GHG emissions of the agricultural sector as a result of their effects on demand are also outside the scope of the study.

• Selection of the ten measures to be examined

The first step in the process to select the measures for in-depth examination during this study was to draw up as exhaustive a list as possible of the agricultural GHG emissions abatement measures examined in existing national and international studies. Following the elimination of "out-of-scope" measures and the combination of technically similar measures, this inventory process led to a list of 35 "candidate" measures (see Section 3).

The measures in this preliminary list were individually examined by the competent expert(s) in the field in order to make an initial assessment of their GHG emissions abatement potential and the availability of scientific and technical references making it possible - or not - to conduct an analysis. The expert group then jointly performed a comparative assessment of these measures in order to progressively select ten measures presenting good properties in terms of the specifications and covering a broad range of agricultural production types. The arguments supporting the elimination of certain measures for in-depth examination were explained.

The interim and final results of this selection process were submitted to the monitoring committee and the technical committee. The interactions with these bodies led to amendment and consolidation of the list of measures to be examined.

• Analysis of the measures selected

The ten measures selected were the subject of joint work to formulate their objective, define their scope and, if applicable, break them down into sub-measures corresponding to a level enabling abatement and cost calculations. Unless otherwise indicated, the abatement potentials of the various sub-measures of a same measure are cumulative.

An assessment of the cost/efficacy ratio of measures, based on the extraction of relevant data from the scientific and technical literature, was then made by the responsible experts and the small expert groups. Hypotheses, methodological choices, data sources, calculation steps and results are presented in the form of one data sheet per measure, split into the following sections:

- a general description of the measure (GHG and agricultural production sub-system concerned, underlying mechanisms, etc.);
- the potential applicability concerned (surface areas or livestock populations to which the measure may be implemented, etc.);
- the expected abatement potential and the cost of implementing the measure;
- the other effects of the measure, assessed quantitatively (effect on production) or qualitatively (effect on other agri-environmental objectives, etc.).

The complete analysis grid for the measures is presented at the end of Section 4.

• Comparative analysis of all the measures and their interactions

The study's two scientific coordinators, along with a small expert group, conducted a comparative analysis of the measures, focusing, in particular, on the following:

- an estimation of the total potential abatement for the agricultural sector in mainland France by 2030;
- comparison of the costs and abatement potentials of the various measures and with the other studies conducted internationally;
- uncertainties, the sensitivity and robustness of the study results.

• Study deliverables

The study deliverables are:

- the study report, composed of a presentation of the methodology, data sheets per measure and a comparative analysis of all the measures. This document, which includes the bibliographic references upon which the analysis is based, is written and signed by the experts;
- the present document, summarising the study and presenting the main results and conclusions;
- an 8-page summary of the study;
- a seminar for presentation of the study results (2 July 2013) open to the scientific and technical community, as well as the stakeholders.

3. Levers for agricultural greenhouse gas emissions abatement and selection of the measures to be examined

3.1. The measure selection process

• Eligibility and selection criteria

The measures for in-depth examination were selected on the basis of eligibility criteria indicated in the study specifications and the expected performance of the measures. The criteria were as follows:

• **Eligibility of the measure with respect to the study specifications.** The measure must concern an agricultural practice - as decided by the farmer - with an expected abatement at least partially located on the farm, involving no major change to the production system and no reduction in production output in excess of 10%. Consequently, any measures focusing on a sector upstream or downstream of the farm (for example, a measure related to food consumption), or targeting the agricultural sector but for which a predominantly upstream or downstream effect is expected (for example, reducing the electricity consumption of the agricultural sector), or which would have a significant impact on national production (reduction in ruminant numbers, significant extension of organic farming), were considered to be outside the scope of the study.

• **Theoretical significance of the abatement potential in the French agricultural context.** Measures for which the potential can be considered to be low due to a modest unitary abatement (because the improvements in practices already achieved reduce the scope for progress, for example) and/or because their potential applicability is limited in France (measure concerning paddy field land to limit CH_4, for example) were not examined. The potential may also be judged to be too uncertain due to a lack of scientific or technical references covering the range of situations on the ground.

• **Current availability of the technology** required to implement the measure and of validated scientific knowledge establishing its efficacy. For example, the following measures were not selected because they are still **at the research phase** and not technically applicable as knowledge currently stands: dihydrogen production from livestock manure to produce energy (not yet technically developed on a farm scale), the incorporation of plant charcoal (biochar) into the soil to serve as a carbon store (process not fully mastered, carbon residence time appears to be highly variable, depending, in particular, on the production process) or crop or livestock adaptations requiring genetic improvements yet to be made.

• **Applicability of the measure**, which can be problematic due to a low technical feasibility on a large scale (modification of the physicochemical conditions of the soil to reduce N_2O emissions on a France-wide scale, for example), "risks" (known or suspected) to health or the environment, incompatibility with current regulations (concerning the use of hormones and antibiotics in farm animals, for example) or a low level of social acceptability (method using transgenesis; elimination of protozoa from the rumen to limit fermentation).

• **Potential synergies or antagonisms with other major agricultural objectives**. This secondary criterion served primarily to consolidate the choice of measures already demonstrating good properties with respect to the previous criteria (erosion control or preservation of land biodiversity, reinforcing the value of no-till cropping systems) or, conversely, to eliminate other measures (involving "intensification" production systems, for example, conflicting with the objectives of reducing the use of inputs).

• A preliminary inventory of candidate measures

The inventory of measures that may potentially reduce GHG emissions, established on the basis of existing national and international studies, is structured around the agricultural activity components concerned (crop production, livestock production, manure management and energy management) and by the GHG emissions abatements sought (target gases: CO_2, CH_4 or N_2O). Four categories (indicated I to IV) have thus been defined, on the basis of the agricultural activity and gases primarily concerned, within which various levers for measure can be employed. This classification of candidate measures also facilitates the incorporation of the objective of a range of measures aimed at ensuring the diversity of agricultural production.

The biophysical mechanisms involved in agricultural GHG emissions and affected by the abatement levers and measures are presented in Box 1.

3.2. The measures selected and the measures not examined

Application of the classification system and then the selection criteria to the 35 measures, illustrates the procedure followed, leading to the selection of ten measures for in-depth analysis (numbered ❶ to ❿) and explains the main reason for elimination of the measures not selected (⊗).

I. Crop production and reduction of soil GHG emissions

This category contains measures targeting biochemical reactions that release N_2O (nitrification and denitrification) and CH_4 (fermentation) in soils, either by modifying physicochemical conditions (primarily aeration) or by reducing fertiliser application.

I.1. Modify the physicochemical conditions of the soil to discourage CH_4 and N_2O-producing reactions

⊗ *Optimise the physicochemical conditions of the soil to limit N_2O emissions* (for example, optimise the pH by liming, limit soil compaction). Measure not retained in the selection since N_2O emissions from soils are the result of numerous factors (intrinsic soil properties, climatic events, human activity) it is not currently easy to predict how changing these parameters would modify N_2O flows and affect these flows on a France-wide scale.

⊗ *Modify the microbial communities of soil by incorporating microorganisms that reduce N_2O into N_2 (incorporation of*

Box 1. Main mechanisms of greenhouse gas emissions and carbon storage in the agricultural sector

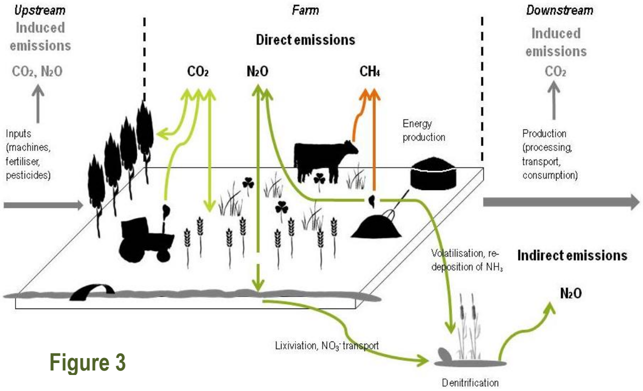


Figure 3

Carbon dioxide (CO_2) emissions

The combustion of carbon molecules (fuel oil, gas, wood, CH_4, etc.), which is accompanied by the release of energy, also emits CO_2. When the carbon molecule is of fossil origin, the CO_2 released accumulates in the atmosphere and contributes to global warming; when it comes from a renewable source, the CO_2 emitted is deemed to have been taken from the atmosphere and thus not to contribute to an increase in atmospheric CO_2 (short carbon cycle).

Combustion is used to produce energy (for example, combustion of CH_4 in a biogas plant), carry out work (e.g. run a tractor) or perform chemical reactions (e.g. synthesis of nitrogen fertilisers). The measures implemented on the farm may lead to a modification in CO_2 emissions outside the farm (a lower consumption of inputs by the farm reduces their upstream production; the production of renewable energy may be used in place of fossil energy downstream of the farm).

Carbon (C) storage

The organic substances produced by photosynthesis - hence from CO_2 trapped from the atmosphere - constitute carbon stocks in biomass, either above ground (stems and leaves) or underground (roots). Following the death of the plant, this organic matter, which remains or is returned to the soil, decomposes under the effect of microorganisms. However, this decomposition process is slow and partial, leading to carbon being temporarily stored in the soil in a variety of forms (microbial biomass, humus, etc.) before mineralisation and return of the carbon to the atmosphere in the form of CO_2. Plant biomass and soil can therefore act as carbon sinks and help reduce CO_2 concentrations in the atmosphere.

The choices made on the farm (land use, cultivation methods used) can modify carbon stores on the farm, as well as outside the farm or even outside France (changing the diet of livestock may have an effect, via soybean cultivation, on deforestation in Brazil, for example).

Nitrous oxide (N_2O) emissions

Some bacteria present in the soil and in livestock manure are the site of biochemical reactions: nitrification converting ammonium (NH_4^+) into nitrate (NO_3^-) and producing N_2O (promoted by aerobic conditions), and denitrification converting NO_3^- into N_2O then N_2 (promoted by anaerobic conditions).

The urea contained in livestock excreta is easily mineralised into NH_3, and its conversion into N_2O is then promoted when some portions are aerobic and others anaerobic (case of aerated solid manure) and discouraged by blocking of nitrification in a completely anaerobic environment (case of liquid slurry). In soil, aeration conditions and organic or mineral nitrogen fertiliser applications (and hence of NO_3^- and/or NH_4^+) have an effect on the reactions and on the production of N_2O. N_2O emissions on the farm are said to be "direct"; emissions occurring in physically linked areas, either following NO_3^- leaching due to water percolation in the soil then denitrification, or following volatilisation of NH_3, re-deposition then nitrification/denitrification, are described as "indirect".

Methane (CH_4) emissions

In anaerobic conditions (without oxygen to allow respiration), some microorganisms use organic substances to obtain their energy by fermentation, emitting CH_4.

In ruminants, the breakdown of carbohydrates (e.g. grass cellulose) in the digestive system (rumen) involves microorganisms that decompose them by fermentation, producing CH_4 that is then eliminated by eructation. When stored in anaerobic conditions (case of slurry), undigested organic matter contained in animal excreta can be converted into CH_4 by fermentation. Finally, in soil that is excessively compacted or water-logged, the lack of oxygen may promote the fermentation of organic matter. Conversely, aerobic soils may oxidise atmospheric methane.

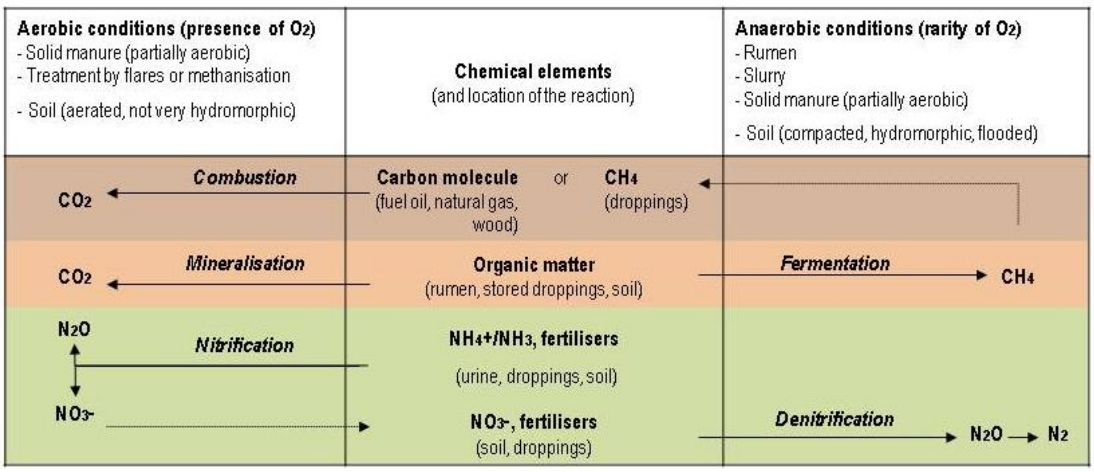


Figure 4: GHG emission sources

Rhizobia strains living in symbiosis with legumes, for example). Measure not retained in the selection because tested in the laboratory and in greenhouses but not yet tested in field trials.

⊗ *Promote aeration of rice-growing soil to discourage fermentation reactions and limit CH_4 emissions* (reduce the depth of paddy fields, empty them several times per year, for example). Measure not retained in the selection despite a not insignificant unitary abatement potential because the potential applicability in France is very limited (around 20,000 ha of paddy fields).

I.2. Reduce nitrogen fertiliser applications on crops

⊗ *Genetically improve the efficacy of nitrogen uptake and use by plants* to enable a reduction in nitrogen fertiliser application. Measure not retained in the selection since it requires work for identification of characteristics and prior genetic selection and hence is not applicable in the short term.

❶ *Reduce the use of synthetic mineral fertilisers, through their more effective use and by making greater use of organic resources*. The potential of this measure is theoretically high since it converges with other agri-environmental objectives and can be quickly implemented. Measure selected.

❷ *Increase the proportion of legumes in arable crops and temporary grassland, in order to reduce N_2O emissions.* This measure can also be applied straight away. Measure selected.

II. Plant production and storage of carbon in soil and biomass

Measures aimed at accumulating organic matter, either by increasing the production of perennial biomass by photosynthesis and/or the amount of organic matter in the soil, or by slowing down its mineralisation.

II.1. Reduce carbon losses by reducing flows from biomass and soil towards the atmosphere

⊗ *Limit the exportation of organic matter out of cultivated fields in order to limit carbon losses from soil* (e.g. do not burn crop residues in the field, but instead return them to the soil). Measure not retained in the selection because its potential applicability is limited since burning is an uncommon practice in France and crop residues are generally already returned to the soil.

❸ *Develop no-till cropping systems to store carbon in soils.* Measure selected because it offers a unitary potential and a potential applicability that are theoretically high (although the subject of debate).

⊗ *Avoid cultivating wet zones to limit the release of CO_2 stored in organic matter*. Measure not retained in the selection despite a not insignificant unitary potential because the amount of cultivated zones that could be returned to wet zones is probably low in France.

II.2. Increase carbon inputs through increased biomass production, thereby increasing flows from the atmosphere towards biomass and the soil

⊗ *Increase the production of biomass by optimising production factors in order to increase the return of carbon to the soil*. Increasing production implies increased fertiliser application or irrigation, which promote emissions of other GHGs. The abatement potential is uncertain and the measure potentially conflicts with other public policies. Therefore it was not retained in the selection.

⊗ *Adjust the selection of cultivated crop species to increase the return of carbon to the soil* (crops with a higher return level, deep-rooted or permanent plants, for example). Measure not retained in the selection since it would have a significant impact on production types and its potential is uncertain, particularly for deep-rooted plants.

❹ *Introduce more cover crops, vineyard/orchard cover cropping and grass buffer strips in cropping systems in order to store carbon in the soil and limit N_2O emissions.* Measure selected.

❺ *Develop agroforestry and hedges to promote carbon storage in soil and plant biomass*. Measure selected.

❻ *Optimise grassland management to promote carbon storage and reduce N_2O* emissions. Measure selected.

⊗ *Restore degraded soil to increase organic matter production and store carbon in soil* (acidified, eroded, saline soils, etc.). Measure not retained in the selection because its potential applicability is limited.

⊗ *Spread "inert" carbon (for example biochars, plant charcoal) on cultivated land to store carbon*. Measure not retained in the selection because its unitary potential is uncertain and the impact on soils and agricultural production is still little known.

III. Livestock production and reduction of CH_4 and N_2O emissions

Measures aimed at fermentation (mainly enteric but also of manure) and nitrification/denitrification of manure, by acting on herd productivity, rumen function or animal nutrition.

III.1. 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.* Measure not retained in the selection due to the high level of compensation between reducing CH_4 emissions and increasing other GHG emissions and because selection on the basis of productivity is already carried out.

⊗ *Select cattle on the basis of residual feed consumption criteria (efficiency of nutrient use) or directly on the basis of CH_4 emissions*. Measure not retained in the selection due to a lack of experience with these selection criteria and lack of knowledge relative to direct selection on the basis of CH_4 emissions.

⊗ *Improve herd management and health to increase livestock productivity*. Measure not retained in the selection because the abatement potential is low given that this approach to herd management is already implemented.

⊗ *Use products that increase per head production (meat or milk)*. Measure not retained in the selection since 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.* Measure not retained in the selection because it would significantly modify livestock farming systems and the potential is uncertain.

III.2. Act on rumen function to reduce enteric CH_4 emissions

⊗ *Regulate populations of microorganisms promoting the production of methane in the rumen using antibiotics*. Measure not retained in the selection because the use of antibiotics for non-curative purposes has been banned in the European Union since 2006.

⊗ *Act on the microorganisms in the rumen by regulating bacteria, protozoa and methanogen populations using biotechnologies*: for example anti-methanogen vaccines, inoculation of specific yeast or bacteria strains, chemical additives (chloride or bromide derivatives) or natural additives (essential oils, plant extracts). Measure not retained because biotechnologies capable of modifying the microbial ecosystem of the rumen are still at the research stage, the other additives have not demonstrated a systematic and long-term *in vivo* effect and some of them have a low level of social acceptability.

III.3. Modify feed to reduce CH_4 and N_2O emissions

⊗ *Modify the nutritional characteristics of forage, favouring non-methanogenic substances to limit enteric CH_4* emissions (increase the sugar or tannin content of forage, etc.). Measure not retained in the selection since still at the research stage; the *in vivo* effects have not yet been demonstrated.

⊗ *Increase the percentage of concentrated feed in the diet*. Measure not retained in the selection due to partial compensations between greenhouse gases and current questions relative to the sustainability of systems based on the use of concentrate-rich diets in ruminants.

❼ *Replace carbohydrates with unsaturated fats and use an additive in the diet of ruminants to reduce enteric CH_4 emissions*. Measure selected.

❽ *Reduce the amount of protein in the diet of livestock to limit the quantity of nitrogen excreted in manure and the associated N_2O emissions*. Measure selected.

IV. Manure management, energy production and consumption on the farm

Measures targeting the production of CO_2 by combustion and manure emissions (fermentation, nitrification, denitrification), either by reducing the use of fossil energy or increasing the production of renewable energy, or by modifying manure storage conditions. Energy consumption as such is not targeted since it is not accompanied by CO_2 emissions of fossil origin on the farm.

IV.1. Reduce the storage or GHG emissions of manure

⊗ *Reduce the amount of livestock manure stored in order to reduce CH_4* emissions due to manure fermentation. Measure not retained in the selection since it has a more limited potential than that of other measures. A proportion of the expected effect is obtained by a sub-measure of measure 6 (extending the grazing period)

⊗ *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 of manure, etc.). Measure not retained in the selection because its abatement potential is uncertain, with a lack of data relating to solid manure systems, in particular.

⊗ *Optimise manure management and storage to reduce N_2O and CH_4 emissions*. Measure initially selected but subsequently abandoned due to technical difficulties examining it.

IV.2. Produce energy from biomass or livestock manure

⊗ *Produce dihydrogen from livestock manure using an anaerobic process and convert it into energy to limit CH_4* emissions and CO_2 emissions resulting from the combustion of fossil fuels. Measure not retained in the selection because research is still being carried out in order to overcome the technical obstacles involved, particularly the chronic instability of the processes.

⊗ *Produce energy on the farm by biomass combustion to reduce CO_2* emissions from the combustion of fossil fuels. Measure not retained in the selection since it is partially covered by measure 5 (conversion of hedge wood into energy). The production of biomass dedicated to energy production is outside the scope of the study.

❾ *Develop methanisation and install flares to reduce* CH_4 emissions related to livestock manure storage. Measure selected.

IV.3. Reduce fossil energy consumption on the 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), etc. Measure not retained in the selection because a significant proportion of the scope of the expected effect is located downstream of the farm.

❿ *Reduce the fossil fuel consumption of agricultural buildings and machinery on the farm to limit direct CO_2 emissions.* Measure selected.

3.3. The ten measures examined

• Measures and sub-measures

Each measure, defined by a lever depending on the areas of the farm concerned and the mechanisms targeted, is divided into sub-measures, corresponding to the various applications of this approach: application to different surface areas or livestock populations, implementation of different techniques contributing to the same objective, etc. In all, 26 sub-measures were thus examined (Table 2).

The abatement potentials of these sub-measures are generally cumulative, insofar as they concern different applicability areas (cattle for one, pigs for another, etc.) or can be applied simultaneously to the same applicability area (compatible modifications in ruminant feed rations or fertiliser application, etc.). However, this additivity is not possible in the case of alternative technical options that cannot be implemented simultaneously. In this case, the different technical options are studied, but only one of them is retained for comparisons between the measures.

• The specific characteristics of the measure selection process

The selection process - the results of which were presented in the previous section - entails a number of specific characteristics in terms of the selection of the measures examined relative to other studies with the same objective (see Section 1) but with different specifications.

The aim of the present study was to determine measures with little or no impact on production systems and for which sufficient information is available to be able to quantify the abatement potential and the cost. This criterion inherently leads to relatively "conservative" proposals, since measures currently at the research stage or for which the effects still appear to be uncertain were eliminated. However, the selection of techniques that are adequately documented means that an in-depth and sufficiently precise analysis of the abatement potential and cost of the measures selected can be conducted.

The selection of measures also reflects social choices, due to the applicability criteria of the measure (in particular, social acceptability, regulations in force, etc.) and consistency with other major agricultural objectives: trend towards changes in agriculture aimed at more economical use of inputs and reducing its impact on the environment (see government programme relating to agro-ecology); reticence on the part of the French population with respect to "biotech" options in agriculture. Conversely, the UK study favours an approach aimed at the intensification of per head production for livestock farming (see point III.1 in the previous section) and the use of "technological" solutions (transgenesis, modification of the flora in the rumen).

Finally, the pre-selection process chosen favoured inclusion on the basis of biotechnical criteria (abatement potential) rather than economic ones (with cost estimations only performed during subsequent examination). This choice may have had the effect of pre-selecting measures with a theoretically high abatement potential (subject to verification) but which will prove to be expensive and, conversely, eliminating measures that are inexpensive but have a low abatement potential. Consequently, the list of the 10 measures selected cannot be seen as a list of measures with the greatest efficiency (cost/abatement ratio) since it was drawn up on the basis of information provided by experts initially, primarily based on abatement potential criteria (and not cost), hence subject to the results of their subsequent examination.

	Measures	Sub-measures
Reduce mineral nitrogen fertiliser applications		
↘ N_2O	**❶ Reduce the use of synthetic mineral fertilisers, through their more effective use and by making greater use of organic resources, in order to reduce N_2O emissions**	A. Reduce the rate of mineral fertiliser by more effectively adjusting yield targets
		B. More effectively replace synthetic mineral nitrogen with nitrogen from organic products
		C1. Delay the date of the first fertiliser application in the spring C2. Use nitrification inhibitors C3. Incorporate into the soil and localise fertilisers
↘ N_2O	**❷ Increase the proportion of legumes in arable crops and temporary grassland, in order to reduce N_2O emissions**	A. Increase the surface areas of grain legumes on arable farms
		B. Increase and maintain legumes in temporary grassland
Store carbon in soil and biomass		
↘ CO_2	**❸ Develop no-till cropping systems to store carbon in soil**	3 technical options: switch to continuous direct seeding, switch to occasional tillage, switch to continuous superficial tillage
↘ CO_2 ↘ N_2O	**❹ Introduce more cover crops, vineyard/orchard cover cropping and grass buffer strips in cropping systems in order to store carbon in the soil and limit N_2O emissions**	A. Develop cover crops sown between two cash crops in arable farming systems
		B. Introduce cover cropping in vineyards and orchards
		C. Introduce grass buffer strips alongside water courses or around the edges of fields
↘ CO_2	**❺ Develop agroforestry and hedges to promote carbon storage in soil and plant biomass**	A. Develop agroforestry with a low tree density
		B. Develop hedges around the edges of fields
↘ CO_2 ↘ N_2O	**❻ Optimise grassland management to promote carbon storage and reduce N_2O emissions**	A. Extend the grazing period
		B. Increase the lifespan of temporary sown grassland
		C. Reduce nitrogen fertiliser application on the most intensive permanent and temporary sown grassland
		D. Improve low productive permanent grassland by increasing livestock density
Modify the diet of livestock		
↘ CH_4	**❼ Replace carbohydrates with unsaturated fats and use an additive in the diet of ruminants to reduce enteric CH_4 emissions**	A. Replace carbohydrates with unsaturated fats in diets
		B. Incorporate an additive (nitrate-based) in diets
↘ N_2O	**❽ Reduce the amount of protein in the diet of livestock to limit the quantity of nitrogen excreted in manure and the associated N_2O emissions**	A. Reduce the protein content in the diets of dairy cows
		B. Reduce the protein content in the diets of pigs and sows
Recycle manure to produce energy, reduce fossil fuel consumption		
↘ CH_4	**❾ Develop methanisation and install flares to reduce CH_4 emissions related to livestock manure storage**	A. Develop methanisation
		B. Cover storage pits and install flares
↘ CO_2	**❿ Reduce the fossil fuel consumption of agricultural buildings and machinery on the farm to limit direct CO_2 emissions**	A. Reduce fossil fuel consumption for heating livestock buildings
		A. Reduce fossil fuel consumption for heating greenhouses
		C. Reduce the fossil fuel consumption of agricultural machinery

Table 2. Measures and sub-measures examined

4. Assessment of the efficiency of abatement measures

4.1. The main variables calculated and the reference situation

• The variables calculated

The abatement potential and cost associated with the measures proposed were calculated in several stages:
1- assessment of the unitary GHG emissions abatement potential (per animal, per hectare, etc.),
2- assessment of the unitary cost,
3- combination of the unitary values to obtain the unitary efficiency of the measure (cost per metric ton of CO_2e avoided),
4- assessment of the potential applicability (number of units, animals, hectares, concerned) and of a scenario for achievement of this potential applicability,
5- combination of the unitary values and the potential applicability to obtain a national-scale assessment over the period 2010-2030.

To take into account the uncertainties associated with the calculations, "ranges" (lower value, upper value) are indicated for the main variables calculated.

These calculations were made on a sub-measure scale, then aggregated by measure when the sub-measures were cumulative.

• The reference situation

The objective being to estimate the potential abatement and cost by 2030, it is necessary to have a baseline situation, i.e. the prevailing situation in the absence of incentives or additional measures aimed at reducing GHG emissions in the agricultural sector. For this, two elements are required: the reference emissions and the baseline scenario (or "without additional measures" scenario). These two elements cannot necessarily be selected independently of one another.

Choosing the **reference emissions** is primarily a matter of calculation convention and can be a source of confusion when it comes to comparing existing studies. In this study, the reference is static and equal to 2010 emissions.

The choice of the **baseline scenario** (surface areas, livestock numbers, yields, prices, etc.) has significant implications, both for the calculation of abatement potentials and calculation of the associated costs. In particular, it requires access to product price and production factor and productivity trajectories. To be usable, these trajectories must be based on *projections* incorporating the effect of measures already in place (or already decided on and scheduled to be implemented at a future date) and exogenous parameters concerning variables liable to evolve independently of any additional abatement measures.
Since none of the projections available meet all the criteria required (availability and completeness of data up to 2030, appropriate scale and data resolution, overall coherence, scenario not including any additional abatement measures), it was decided to examine the consequences of the abatement measures on the basis of the situation prevailing in 2010.

All the abatement potentials were therefore calculated relative to the reference emissions for 2010. This choice means that reference can be made to the emissions and calculation methods of the most recent available inventories published by the CITEPA. It is therefore necessary to consider the abatement potentials and costs calculated in this study as being the effect of the abatement measures examined on the basis of *a constant technological context and price system*.

The decision to opt for a historical static reference makes it possible to draw on available data for examination of the measures and inherently ensures overall coherence between cropping systems, production and consumption volumes and the pricing system. Finally, in a context of significant uncertainties with respect to evolutions in agricultural policies, this choice makes it possible to avoid adding the uncertainty inherent in the construction of a reference scenario to the uncertainty already surrounding the effect of the abatement measures itself.

4.2. Estimation of the emissions abatement potential of the measures

• The scope and the emissions taken into account

The measures selected on the basis of an expected abatement in GHG emissions on the farm are also liable to modify emissions upstream and downstream of the farm, due to the resulting modifications in the inputs used or in the outputs. This therefore raises the question of defining the system that the abatement calculations will concern. Two approaches are traditionally used: the "source-sink" approach, which quantifies net emissions occurring on a defined area (a farm, for instance), and the "life cycle analysis" (LCA) approach, which evaluates the environmental impacts of a system at the origin of a product or service, from extraction of the raw materials required to produce it right up to its treatment at the end of its lifetime.

In the context of this study, a "source-sink" analysis - also used for the national GHG emissions inventory - was favoured. The scope of the systems considered, the emission sources recorded and the methods for calculation of the expected abatements were selected such that it is possible to refer to the emissions categories and values calculated in the context of the inventory.

However, these calculations were supplemented by information on significant modifications in emissions induced upstream or downstream of the system considered. Without aiming to achieve the exhaustive nature and precision of an LCA approach, this information makes it possible to discuss the limits of the quantification performed using the "source-sink" methodology.

In this approach, a differentiation can be made between two types of emission modifications:

- those concerning emissions **occurring within the farm** (known as **direct emissions**) **and those in physically linked areas** (known as **indirect emissions**; for example, N_2O emissions occurring in ditches and wet zones located downstream of fields, following leaching of nitrates);

- those affecting emissions **induced upstream or downstream of the farm**, due to implementation of the proposed measure.

Upstream, for example, these may be CO_2 emissions linked to energy consumed for the production of mineral nitrogen fertiliser or animal feeds purchased by the farmer. Downstream, they may be CO_2 emissions avoided thanks to energy produced on the farm (case of methanisation) and used outside it.

Modifications in direct and indirect emissions were listed and quantified as accurately as possible; those induced upstream or downstream of the farm were listed and quantified using the reference values available in databases.

• The unitary potential calculation method

For each measure, following identification of the farm sub-system concerned (cultivated surface area, livestock buildings, etc.), all the GHG emission sources modified by the measure and the gases concerned (CO_2, CH_4, N_2O) are recorded, differentiating, firstly, between direct and indirect emissions and, secondly, emissions induced upstream or downstream of the farm. The unit chosen to express the unitary potential is adapted to the nature of the measure (emission per hectare, per animal, per manure mass unit or building surface area, etc.). N_2O and CH_4 emissions are expressed in "CO_2 equivalent" (CO_2e), taking into account their global warming potential (GWP).

Irrespective of the level considered, the general principle for the estimations is based on "**emission factors**" (Figure 5). An emission factor is a multiplying coefficient used to estimate the quantity of GHG emitted as a result of a human activity, i.e. to go from measurement of this activity to measurement of the greenhouse gas effect it causes. In national inventory calculations, the equations contain several emission factors corresponding to the various emitting mechanisms and for which the values sometimes incorporate the environmental conditions (temperature, etc.) or the management method (of waste, for example). It is when selecting these values, on the basis of conditions or management methods, that it is possible to take into account - or otherwise - the effects of a measure in the calculations.

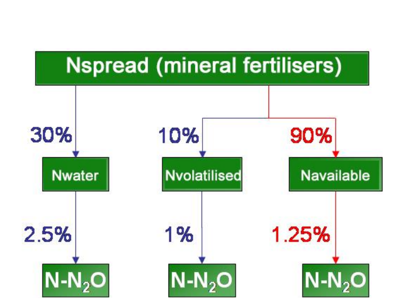


Figure 5. Example of an N_2O emissions calculation diagram in the current CITEPA method (IPCC 1996).

The overall emission factor to be applied to the amount of nitrogen applied in the form of mineral fertilisers is 1.975% in this example.

For direct and indirect emissions, these were quantified as accurately as possible for all the modified emission sources and all the gases (difference between emissions with and without the measure). Two calculations were made:

- One calculation with the method, equations and parameters used for the CITEPA's 2010 national inventory of emissions (according to 1996 IPCC guidelines). This first calculation makes it possible to refer to the emission values from the 2010 inventory and to place the calculated abatements in this context. Its very significant limitation is that the equations used cannot, by their very nature, indicate the expected abatement of certain measures (those concerning no-till cropping systems or animal nutrition, for example). For the purposes of consistency with the CITEPA inventory, this calculation was performed using the old GWP values (GWP_{CH4} = 21 and GWP_{N2O} = 310);

- An "improved" calculation, proposed by the experts, correspond-ding to the most accurate estimation possible given current knowledge and on the basis of the references available in the literature. Depending on the emission sources and the measures, this may involve a calculation consistent with the IPCC guidelines published in 2006 or based on these, or a more complex calculation, based on the bibliographic analysis performed by the experts. Where the data make this possible, calculations take into account the diversity of situations, differentiating between grassland categories on a regional basis, for example, or between livestock categories according to their diet. This second calculation offers the benefit of evaluating the expected abatement of the measures as accurately as possible, but makes comparisons with the emissions calculated in the inventory difficult. This "expert" calculation was performed using the GWP values updated in 2006 (GWP_{CH4} = 25 and GWP_{N2O} = 298).

For emissions induced upstream and downstream of the farm, quantification was only performed for the most significant and substantially modified emission sources, for which the magnitude of the emission modifications could affect the conclusions reached as a result of the calculations performed on direct and indirect emissions alone. These modifications induced upstream and downstream were calculated using standard emission factors linked to products or services, taken from reference databases (the ADEME's Base Carbone® and the Dia'terre®-Ges'tim database).

For measures leading to an emissions abatement that is reproducible year on year (fertiliser application, animal nutrition, etc.), the unitary abatement potential is expressed in tCO_2e per unit and per year. For measures leading to an abatement that is variable over time (measures concerning increased carbon storage in soil or tree biomass), the relatively short duration of the period considered (20 years) meant that it was possible to perform a linear approximation of the abatement values. These were therefore expressed in constant quantities of CO_2e per unit and per year, making comparison between measures easier.

4.3. Estimation of the cost of the measures

• The scope and nature of the costs taken into account

For each (sub)-measure, the loss or gain to the farmer due to the technical modifications implemented on the farm is calculated. However, the development of a measure requires the implementation of incentive and regulatory measures (regulations, taxation, subsidies, etc.), which can represent a cost to the public authorities (for the design, implementation, monitoring, assessment stages), but also to the farmers themselves (time spent finding information, obtaining training, completing paperwork, etc.). The former costs are public transaction costs; they are not calculated in this study since they are largely dependent on the incentive or regulatory mechanism chosen, the determination of which does not fall within the scope of this study. The latter correspond to private transaction costs; they are also dependent on the incentive mechanism selected, but to a lesser degree. They were estimated in order to supplement calculation of the cost to the farmer.

Box 2. The data used to perform the calculations

The data requirements associated with the main three calculations to be performed are as follows.

***The unitary emissions abatement calculations** require knowledge of crop and herd management practices, the emissions coefficients used by the CITEPA or taken from the literature, and the emissions induced by measures upstream/downstream of the farm to supplement the "source-sink" calculations.*

***The calculations for the unitary costs of the measures** require knowledge of the prices of inputs and agricultural outputs, livestock and crop yields, margins per hectare of certain agricultural products (difference between income and expenditure for a hectare of a given crop), operational costs (labour, farm machinery), purchase cost, lifespan and maintenance costs of specific equipment that farms need to invest in for certain measures.*

***The potential applicability calculations** require data concerning the surface areas of various crops, the proportion of cultivated surface areas with characteristics compatible with the measures studied, livestock numbers and the number of farms with relevant characteristics for the measures studied.*

The data sources required must be available (existence and accessibility) on a mainland France scale (with regional or departmental data if applicable) for the reference year (2010), be homogeneous between the measures and consistent with one another.

The main data sources common to all the measures are obtained from the French Ministry of Agriculture's Department of Statistics and Forward Studies (SSP):
- annual farming statistics (SAA) 2010,
- the agricultural accounting information network (RICA) 2010. The RICA sample is representative of large and medium-sized farming operations; it covers 64% of all farms, but 93% of the utilised agricultural area (UAA) and 97% of production potential (standard gross production or SGP).

The SAA does not contain any information on the farms, nor on the distribution of surface areas and livestock populations within the different farm categories, unlike the RICA. Each time that a measure only concerned the figures (surface areas or livestock numbers) for a certain type of farm, the corresponding national figure percentage was determined on the basis of RICA 2010 data, then applied to the SAA figures.

*Neither the RICA nor the SAA specify **crop management practices** (doses, frequencies and forms of nitrogen fertiliser application, for example.) or **livestock farming practices** (feed rations distributed to animals, manure management methods, etc.). The experts used the "Cropping practices" survey (performed by the Department of Statistics and Forward Studies (SSP)) from 2006 (since the data for the 2011 survey were not yet available at the time of the study). Regarding livestock farming practices, the experts often drew on the expertise of technical institutes: use of the dairy cow feed ration typology employed by the Institut de l'Elevage (Institute of Animal Husbandry), data regarding swine nutrition systems from the Institut du Porc (Pig Institute), the "Livestock buildings" survey carried out by the Ministry of Agriculture (Department of Statistics and Forward Studies - SSP) for the manure management method, etc.*

*For the **GHG emissions** taken as the reference values in the calculations, the experts used the CITEPA inventory for 2010 (published in 2012), for mainland France.*

*As regards **costs**, the RICA database contains economic information - for example on product volumes in terms of quantity and value - that was used to calculate 2010 prices for livestock and crop products and estimate the margins of the main crops. The following were also used more occasionally: the Eurostat database for the price of nitrogen fertilisers, or CUMA (machinery cooperative) mutual aid scales for the costs of crop management operations (ploughing, fertiliser spreading, etc.).*

Type of calculation	Data requirements	Sources
Abatement calculations	Crop management practices (fertiliser application, tillage, etc.)	"Cropping practices" survey (Agreste - 2006)
	Animal feed rations	Technical institute references: Institut de l'élevage (IDELE), Institut du porc (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	RICA (Agreste - 2010)
	Fertiliser prices	Eurostat
	Economic margins	Agricultural accounting information network (Réseau d'information comptable agricole - RICA) (Agreste - 2010)
	Cost of cultivation operations (ploughing, etc.)	CUMA (machinery cooperative) mutual aid scale 2010-2011
Potential applicability calculations	Crop surface areas	Annual farming statistics (SAA) (Agreste - 2010)
	Livestock numbers	
	Yields	RICA (Agreste - 2010)
	Land characteristics and use	Geographic database for land use in France on a scale of 1/1 000 000 (BDGSF), and European land cover map (*Corine Land Cover*)

Table 3. Data sources used per calculation type

The costs (positive or negative) calculated for farmers correspond to the **average** unitary costs for the "French farm", and not the marginal costs or opportunity costs of the last farming operation implementing a given measure. They are calculated without re-optimisation of production systems and without considering the indirect impacts that measures could have on the operation of farms, the macro-economic balances on a national scale (modification of the diet of the French herd, re-focusing of crop production and hence the effect on the price ratios of agricultural products) or on farmer behaviour (re-adjustment of practices in response to the implementation of the measure and hence possible reduction in certain shortfalls).

• The unitary cost calculation method

In line with the baseline scenario selected, the price system used corresponds to the prices of inputs and outputs in 2010.

The loss or gain to the farmer is calculated considering: the increase or decrease in variable costs (fertilisers, pesticides, livestock feed, labour, contractor services, etc.), the increase or decrease in yields (milk, meat, crop) and hence associated income, loss of income due to the change in activity (crop substitution, for example), any new income generated (purchase by EDF of electricity produced, for example), and clearly identified investments (purchase of a biogas plant, etc.). The cost of the measure is expressed in euros per year and per hectare of crop, head of livestock or farm.

This loss or gain includes subsidies when these cannot be separated from the price paid by or to the farmer (subsidised purchase of electricity produced by methanisation, price of agricultural fuels benefiting from a tax exemption, for example). It does not take into account single payment entitlements (SPEs), coupled CAP aids, or optional subsidies, which are often local. The cost, which makes it possible to analyse the measures in the 2010 reference context, is nonetheless supplemented by a calculation not including the subsidy in cases in which this significantly modifies the results, enabling a comparison that does not take into account incentives already in place.

The calculations differ between: firstly "annual" measures, for which the costs and gains are identical year on year (adjustment of fertiliser application, for example) and, secondly, measures requiring an initial investment and with costs and revenues that are irregular or delayed (for example, agroforestry or manure methanisation). In the second case, and in order to be able to compare the measures with one another, the constant unitary loss or gain is calculated, which, over the duration of the measure, would be equivalent for the farmer (equivalent constant annuity). This calculation requires the use of a discount rate, the choice of which is difficult and controversial given the apparently lasting stagnation of growth. The rate chosen is the 4% rate proposed by the Centre d'analyse stratégique (Centre for Strategic Analysis) (which has since become the Commissariat général à la stratégie et à la prospective - General Commission for strategy and forward studies) and indicated by the Commissariat général au développement durable (CGDD - General Commission for sustainable development).

The transaction costs for the farmer generally correspond to the time spent implementing the measure (information searches, administrative documents to be completed, etc.). Due to learning effects, these costs tend to decrease over time. An approximation of these costs was obtained by adapting the results of a study proposing a calculation formula based on the implementation of agro-environmental measures (Box 3).

Box 3. The private transaction cost (PTC) calculation method

*PTCs were calculated for each sub-measure using a model taken from the European ITAES (*Integrated Tools to design and implement Agro-Environmental Schemes*) project, aimed at improving the development and implementation of agro-environmental measures (AEMs). This project measured the transaction costs to farmers having adopted an AEM directly, as well as indirectly through analysis of the adoption of these measures. It demonstrated the weight of PTCs in the total cost of complying with the measures adopted and the significance of their anticipation by farmers in terms of decisions not to adopt an AEM. The model developed to calculate PTCs takes into account the general education of the person in charge of the farm and the standard gross production (SGP) level concerned by the measure; PTCs decrease as the education level and SGP level increase.*

This model was used to calculate the average PTC on all farms, then per potential applicability unit, for each sub-measure. Data from the RICA 2010 database were used to select farms presenting relevant characteristics for the measure and calculate the SGP concerned by it. This method provides a rough approximation of PTCs, since, firstly, all the farm selection criteria are not indicated in the RICA database and, secondly, all the measures do not fall within the validation scope of the formula. It is nonetheless useful to take them into account since they may be decisive when it comes to the adoption - or not - of certain measures.

4.4. Estimation of the measure adoption potential on a France-wide scale and up to 2030

• Determination of the measure's potential applicability

When it comes to potential applicability, a distinction is made between two quantities:

- **the theoretical potential applicability (TPA)**, corresponding to the scope to which the measure can be applied if potential technical obstacles are not taken into account. For example, for a measure on ruminant nutrition, the theoretical potential applicability is the entire ruminant population;

- **the maximum technical potential applicability (MTPA)**, which is smaller than the theoretical potential applicability, without technical contraindications or unfavourable side effects, and in conditions that are technically acceptable to farmers. These different restrictions lead to certain crop or soil types being subtracted from the potential applicability of direct sowing, for example: root crops (requiring soil tillage) and poorly drained soils (for which N_2O emissions increase in no-till cropping systems); or limit the MTPA of a measure concerning animal nutrition to livestock categories in which the diet can be applied in conditions that are technically acceptable to the farmer.

• **The measure adoption scenario**

The development of the measure on a France-wide scale is connected to the innovation dissemination phenomenon; studies in the agricultural sector have shown that the rate starts slowly, then rapidly increases before slowing down again and disappearing once adoption is maximal (sigmoid curve). The selection of an adoption scenario based on these kinetics for each (sub)-measure requires the determination of four characteristics (Figure 6):

- the reference situation in 2010 (measure X already implemented for part of the potential applicability, measures Y and Z marginal in 2010);
- the percentage of the MTPA that could reasonably be achieved by 2030 (measure Z reaching 60% of the MTPA in 2030);
- the point at which the measure actually begins to develop (start of adoption from 2010 for measures X and Y, and 2018 for Z);
- the point at which the measure reaches its adoption peak (peak reached in 2030 for measures X and Y, and 2028 for Z).

These adoption characteristics are defined on the basis of information provided by experts, taking into account the numerous factors that might slow down, limit or delay adoption of the sub-measure: an unfavourable economic context, a lack of available equipment, reluctance to make a long-term commitment (agroforestry), organisational difficulties related to the measure on the farm, inadequate funds limiting investments, problems related to acceptability to society or consumers (measure excluded by certain labels), etc.

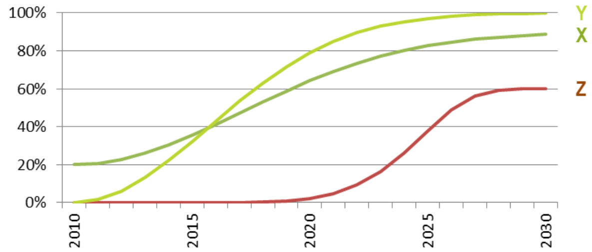


Figure 6. Different adoption scenarios (sigmoid curves), attaining the MTPA - or otherwise - by 2030

The construction of this adoption scenario for the measure is not intended as a forecasting tool but, rather, to perform calculations within the context of hypotheses that are as realistic as possible. However, in order to determine an abatement "potential", the measure dissemination hypotheses adopted are deliberately relatively "optimistic".

4.5. Calculation of the abatement potential, cost and efficiency of the measures

The foregoing calculations of the abatement potential and unitary costs, maximum technical potential applicability and adoption kinetics make it possible to assess the abatement potential and cost of implementing the measure on a national scale in France over the period 2010-2030, and then to determine its efficiency.

The abatement potential in 2030 of a measure is obtained by multiplying its unitary potential by the scope attained in 2030 (the year at which it reaches its peak). Its cumulative potential over the period 2010-2030 is the sum of the annual abatements, calculated by multiplying the unitary abatement by the converted annual portion of the potential applicability. The abatement is calculated using the CITEPA method, then the "expert" method, with the latter then being supplemented by the induced effects.

The total annual cost in 2030 of a measure is obtained, in a similar manner, by multiplying its annual unitary cost by its national potential applicability for the year considered. Its cumulative cost over the period 2010-2030 is the sum of the annual costs and therefore takes into account the adoption kinetics. This involves the cost to "the farmer" in the absence of any new state aids and without taking into account private transaction costs, the significance of which is discussed in Part III.

The cost, to the farmer, per metric ton of CO_2 avoided, enables the measures to be compared with one another, but also with carbon market prices. Given the multiple calculation options possible (CITEPA or "expert" calculation, with or without induced emissions, with or without private transaction costs, etc.) choices were necessary to enable comparison between the measures. The cost per metric ton of CO_2 avoided was calculated using the "expert" method, excluding induced emissions and excluding private transaction costs. The effect of different calculation methods is nonetheless discussed.

These variables are calculated per sub-measure, then determined on the scale of the measure when the various sub-measures are cumulative, taking into account any interactions between them. However, this addition of the effects and costs cannot be performed between several technical options (by definition not cumulative).

The two variables traditionally used to compare the measures are the annual abatement potential and the cost per metric ton of CO_2 avoided; a graph for each measure, depicting the abatement potential (on the x-axis) and the cost per metric ton of CO_2 avoided (on the y-axis), then provides a summary view of the comparative efficiencies.

4.6. Context of results

The objective of the last part of the analysis is to put the results into context and perspective, recalling the "limitations" of the exercise that must be borne in mind when interpreting the quantitative data and indicating the additional elements that will be involved in implementation of the measure.

The sensitivity of the results to the hypotheses. Since the quantitative assessments are dependent on the conditions considered and the hypotheses adopted to perform the calculations, it is important to assess the impact of these choices, which are a source of disparities in the results, or even controversy, with respect to the benefit that a measure may offer. This sensitivity of the results to the hypotheses was explored by performing calculations with low and high values for certain variables (unitary emissions, price levels, potential applicabilities, etc.), or by occasionally testing the impact of the value used for some parameters.

The conditions for incorporation of the measure in the national inventory. For the measure to be counted, the method used to establish the national inventory needs to include calculation rules and parameters (emission factors, etc.) enabling the effects of the measure to be taken into account and quantified. But for a country to claim a measure, it is also necessary to be able to verify its implementation: it must be possible to establish that the measure has been implemented on the basis of a reliable data source (official statistics, CAP declarations, etc.) and to verify it in the field (verification of cropping sequences by satellite images).

The contexts and measures liable to promote the roll-out of the measure. While the study specifications excluded the development of proposals for regulatory or incentive measures aimed at increasing the adoption of the measure, it is interesting to indicate the contexts - economic, in particular (input our output price evolutions, etc.) - and the existing policies and measures (environmental measure plans, CAP measures, etc.) liable to encourage its adoption.

Vulnerability and adaptability of the measure to climate change. These characteristics are also likely to affect the interest and applicability of the measures in the longer or shorter term.

Other effects of the measure, excluding GHGs. These other impacts - environmental, in particular - may reinforce the interest of a measure (and contribute to its funding) or, conversely, qualify them.

The "data sheets" that follow (Part II) present a synopsis of: the measure and the mechanisms it involves, the hypotheses, calculation rules and data used to perform the abatement and cost estimations, the main results and the elements required to put the measures into perspective. The information in full, including the bibliographic references used and details of the calculations, in particular, can be found in the study report (Box 4).

Box 4. The analysis grid for each measure in the study report

Introduction. *Presentation of the farm or agricultural practice sub-system targeted by the measure, mention of the main greenhouse gas emitted by this sub-system and explanation and objective of the measure.*

1. Description of the measure*. Presentation in terms of agricultural practices, brief description of the mechanisms or phenomena involved, explanation of the scope of the measure (sub-measures and technical options), information on existing reports or expert assessments having examined this measure.*

2. Underlying phenomena/mechanisms*. Inventory of current knowledge concerning the mechanisms, based on an analysis of the international scientific literature (demonstration of the mechanism, orders of magnitude relative to emissions, uncertainties, determining factors).*

3. Link with the national emissions inventory*. Explanation of the inventory category counting these emissions. Description of the effect of implementing the measure on the emissions estimated in the inventory and of the calculation method enabling its quantification, if applicable (Tier 1, 2, or 3).*

4. Estimation of unitary abatement potential*. Compilation of an inventory of expected effects of the measure on gas-emitting mechanisms. Determination of the abated emission factor that will be used for each of these effects, expressed per unit and per year (e.g.: ha/year, animal/year, etc.).*

5. Baseline and development conditions for the measure*. Description of the current dynamic regarding this measure, analysis of the technical and agronomic conditions required to implement it and expression of the resulting maximum technical potential applicability on a national scale in France (e.g. in ha, in livestock numbers, etc.), determination of adoption kinetics from 2010 to 2030.*

6. Calculation of the abatement potential on a national scale in France*. The unitary abatement potential, the maximum technical potential applicability and the adoption kinetics of the measure (annual share of surface area on which the measure is implemented from 2010 to 2030) can be used to calculate the potential abatement due to the measure on a national scale in France from 2010 to 2030 (in quantities of CO_2 equivalent/year).*

7. Calculation of costs*. Determination of the unitary cost to the farmer induced by the measure, then, using the maximum technical potential applicability and adoption kinetics, determination of the cost to all French farmers.*

8. Other effects of the measure*. Indication of the other effects on food production (quality, quantity) and on the environment, indication of interactions with existing or pending public policies, description of potential interactions with the other measures selected in the study.*

Conclusions*. A review of the results of the abatement and cost calculations on a mainland France scale and expression of the measure's efficiency. Discussion of the results in terms of uncertainties, the other effects of the measure and interactions with other measures.*

Part II

Analysis of the ten technical measures

↘ N_2O

1 Reduce the use of synthetic mineral fertilisers, through their more effective use and by making greater use of organic resources, in order to reduce N_2O emissions

A. Reduce the rate of mineral fertiliser by more effectively adjusting yield targets
B. More effectively replace synthetic mineral nitrogen with nitrogen from organic products
C. Improve the efficiency of mineral nitrogen in fertilisers by modifying the application conditions

I- Challenge and principle of the measure

In France, N_2O emissions by agricultural land were estimated to represent 46.7 million metric tons of CO_2 equivalent ($MtCO_2e$) in 2010, i.e. 44% of emissions from the agricultural sector. These emissions are particularly associated with the use of synthetic nitrogen fertilisers. There is now a consensus with respect to the significance of excess nitrogen in cultivated systems in France, the low overall efficiency of the nitrogen supplied to the soil by synthetic mineral fertilisers and, finally, the potential for good farming practices to improve the situation.

This measure is designed to study the possibilities of reducing N_2O emissions by simultaneously reducing synthetic fertiliser doses and emissions per unit of nitrogen supplied. The levers for measure studied are: reducing the rate of mineral nitrogen applied by better adjusting yield targets, making better use of livestock manure and other organic waste in place of mineral fertilisers, and improving the efficiency of the nitrogen supplied by modifying the application conditions. None of these techniques affect yields or involve any major change to production systems.

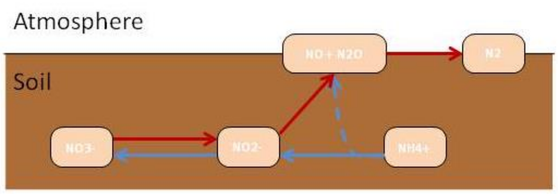
Reducing mineral fertiliser application also leads to fossil energy savings (and hence reduces CO_2 emissions induced upstream of the farm), since the manufacture of synthetic nitrogen fertilisers requires large quantities of energy.

The measure concerns arable crops, excluding legumes. It is complementary to other measures also aimed at reducing mineral nitrogen fertiliser application, via: increasing legume crop surface areas (Measure 2), extending the use of cover crops limiting losses (sub-measure of Measure 4) or "de-intensification" of the most fertilised grassland (sub-measure of Measure 6).

II- Mechanisms and technical methods of the measure

• N_2O emissions and nitrogen fertiliser application

The level of N_2O emissions (Figure) released by soils is highly variable. It depends on numerous factors: the nature of the products applied (mineral or organic fertilisers, mineral fertiliser forms), the soil type and condition (aerobic or anaerobic conditions), synchronisation between the availability of mineral nitrogen in the soil and the crop's uptake capacities. However, global analyses of N_2O flows from soil demonstrate that in arable systems, the amounts of nitrogen provided to soils determine the intensity of N_2O emissions. Hence the methodologies for estimating **N_2O emissions by cultivated land, on a national scale, are based** on knowledge of the amount of nitrogen fertiliser applied.



Biological processes involved in N_2O emissions by soils: nitrification (red arrows) generally observed in aerobic conditions and denitrification (blue arrows) in anaerobic conditions

The application of nitrogen fertiliser leads to "direct" N_2O emissions - i.e. emissions by soil in fields to which fertilisers are applied - and "indirect" emissions, occurring in other sections of the environment following transportation (nitrate leaching or volatilisation then re-deposition of ammonia) of the nitrogen applied to the field.

• Current nitrogen fertiliser application practices

France is in a position of significant mineral nitrogen surplus. Farming activities generate an average surplus of 36 kg of nitrogen per hectare per year, representing a quarter of the nitrogen fertiliser applied in total. These average values cover marked regional disparities: the surplus has increased substantially in eastern France, whereas it is decreasing significantly in the livestock-farming regions of western France. However, the surplus is still high in the latter regions, since the nitrogen supplied by organic manure is only partially deducted from the nitrogen rate to be applied in mineral form.

Despite three decades of research into nitrogen fertiliser application practices, the most recent studies indicate that one of the major problems remains the low efficiency of the nitrogen supplied: on average, less than half of the nitrogen supplied by a fertiliser is taken up by the crop, with the remainder being lost via gas emissions (ammonia, NOx, N_2O, N_2) or leaching (nitrate), or used by microorganisms in the soil. However, more effectively synchronising nitrogen application with plant requirements helps crops make better use of fertilisers. This knowledge has led to the development of dose-fractioning (more numerous applications), which has nonetheless not been reflected in a reduction in total nitrogen rates. The use of fertiliser application calculation or management tools is not generally accompanied by a reduction in the amount applied. This situation is due, in particular, to frequent over-estimation of yield targets and hence the crop's nitrogen requirements.

• The sub-measures studied

The measure was explored via 3 levers converted into sub-measures.

A. Reduce the rate of mineral nitrogen applied by more accurate assessment of crop requirements.

The mineral fertiliser rate can be better adjusted to crop requirements by setting more realistic yield targets. This sub-measure is accompanied by greater use of nitrogen fertiliser application management tools.

B. Make better use of organic product (livestock manure and other waste) application in order to more extensively replace synthetic mineral nitrogen with nitrogen from organic products and thus reduce the use of synthetic nitrogen fertilisers. Three possibilities are studied:

B1. Improve the incorporation of organic nitrogen provided in nitrogen balance calculations.
B2. Improve the efficiency of organic applications by reducing losses due to ammonia volatilisation during spreading operations thanks to systematic incorporation of manure.
B3. Increase the volume of recycled waste, by using additional non-agricultural resources (water treatment plant sludge, agro-industrial or urban waste, etc.).

C. Help crops make more efficient use of the mineral nitrogen applied by modifying fertiliser application techniques.

C1. Delay dates of fertiliser application until early springtime in winter crops, more effectively taking into account residual mineral nitrogen content in the soil at the end of winter.
C2. Use nitrification inhibitors associated with fertiliser nitrogen to achieve nitrogen supply kinetics that are better tailored to the plant's requirements.
C3. Incorporate mineral fertilisers into the soil when sowing spring crops to limit losses, particularly due to volatilisation.

These proposals do not lead to any reduction in production. It should be noted that the complete study (see the report) also assessed the abatement achieved by the reduction of nitrogen fertiliser application associated with the reduction of plant health products, in line with the principles of the national "Ecophyto 2018" programme; this option leads to a moderate reduction in yields. However, the study did not examine the scenario of the development of organic agriculture (using no synthetic fertilisers), since this leads to yield reductions that are variable but often greater than the 10% threshold set in the study specifications.

The measure applies to arable crops, excluding legumes and temporary grassland (in rotation with annual crops), which are the subject of specific measures in this study (Measures 2 and 6).

• Other effects of the measure

Modifying fertiliser application practices can affect the number of nitrogen spreading operations (fractioning of doses), spreading techniques (solid or liquid fertilisers, incorporation into the soil or surface applications), as well as the forms of nitrogen applied. These modifications in practices affect direct CO_2 emissions linked to the diesel consumption of agricultural machinery and, upstream, "induced" emissions linked to the production and transport of inputs. It is important to consider this "upstream" source when evaluating the measure, since the manufacture and transport of nitrogen fertilisers are directly related to the fertiliser requirements of farms.

By helping to reduce surplus nitrogen, the measure is also liable to reduce "downstream" emissions induced by the management of the effects of these surpluses (water treatment, management of green algae proliferation, etc.); however, these effects will not be analysed or incorporated.

III- Calculations of the abatement potential and cost of the measures

• The systems and data sources used

The information on current fertiliser application practices, required to put forward appropriate agronomic solutions and quantify their effects, is derived from the 2006 "Cropping practices" survey (since the results of the 2011 survey were not available at the time of the study). These data cover the main arable crops in France; the few more secondary crops not included in the survey are not taken into account therefore. The surface area data are obtained from the 2010 Annual farming statistics (SAA).

The agronomic situations, technical methods and effects on mineral fertiliser application of the sub-measures are indicated hereafter.

A. The setting of more realistic yield targets for the various arable crops (in view of the yields actually obtained) concerns a potential applicability of 11.7 Mha. It leads to an average rate reduction of 20 kgN/ha, i.e. 10 to 15% of the total amount; sugar beet is excluded, since fertiliser application to this crop has been reduced due to its negative effects on quality. The reference situation (2006 data) is an application of the balance method on 2/3 of surface areas already, and a fertiliser application management tool on 7% of surface areas.

B1. Taking organic nitrogen more effectively into account when calculating the balance leads to an average mineral nitrogen saving of 5 kgN/ha.

B2. Incorporation of organic fertilisers is performed using spreading equipment with integrated drop hoses and grinders. In addition to reducing ammonia volatilisation, this leads to estimated fertiliser savings of 7 kgN/ha.

B3. The "reservoir" of nitrogen-rich organic products that can be used by agriculture is estimated to be around 180 000 tN/year by ADEME, i.e. twice the quantities currently applied. Making use of this would lead to estimated mineral fertiliser savings of 2 kgN/ha.

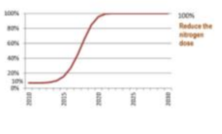
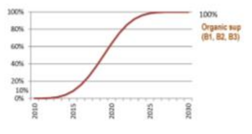
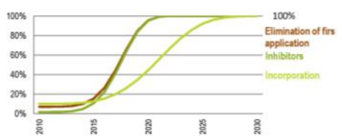
For B, the potential applicability concerns 12 Mha. The abatement potential was only estimated on a global basis for France as a whole, given the diversity of local situations concerning the substitution between mineral fertilisers and organic waste products. This method should not affect estimation of the overall abatement potential too much but it probably leads to the costs being under-estimated, since the transfer of materials to user farms is not taken into account.

C1. The objective of delaying nitrogen application in the spring for winter crops means eliminating the first application and transferring a proportion of the first fertiliser dose to the next application. The share of winter crops (wheat and barley, oilseed rape) presenting significant residual nitrogen at the end of winter was estimated on the basis of regional soil analysis data. The reduction in dose is estimated to be 15 kgN/ha for a potential applicability of 1.8 Mha.

C2. The technical option studied is the addition of a nitrification inhibitor (the product taken as the references is DMPP, primarily used in market gardening at present). Given that a proportion of the nitrogen needs to remain rapidly available to the crop, the inhibitor is only combined with a fraction of the nitrogen applied. The reduction in total dose is 10 kgN/ha for a potential applicability of 2.3 Mha.

C3. Localised placement by incorporation into the soil of fertilisers is applied to spring crops receiving solid fertilisers at the time of sowing. This requires modification of spreading equipment (or the use of a contractor). The reduction in total dose obtained is 12 kgN/ha for a potential applicability of 3.7 Mha.

The sub-measures can be combined: on winter wheat, for example, combining A, C1 and C2 reduces the amount of mineral

	Sub-measures	A. Reduce the nitrogen rate	B. Make better use of organic fertilisers	C. Improve the efficiency of nitrogen		
Technical content	**Initial situation**	Surplus mineral nitrogen application, due to over-estimation of yield targets	Organic fertilisers inadequately incorporated in calculation of fertiliser application, and under-used	Low efficiency of mineral nitrogen applied (losses due to nitrate leaching and ammonia volatilisation)		
	Fertiliser application management proposed	**A.** Calculate the nitrogen balance using more appropriate yield targets	**B1.** Take organic N more effectively into account **B2.** Reduce losses due to volatilisation **B3.** Increase recycled waste volumes	**C1.** Delay of the first N application	**C2.** Use nitrification inhibitors	**C3.** Incorporate fertilisers into the soil
	Resulting mineral fertiliser reduction	19.7 kgN/ha (14.8 to 29.4)	B1 + B2 + B3: 14.4 kgN/ha (9.8 to 22.2)	15 kgN/ha	10.2 kgN/ha	12.3 kgN/ha (0 to -18.4)
Unitary abatement potential		Lower amount of nitrogen applied and/or better efficiency				
	N_2O emissions* (direct + indirect) $kgCO_2e$/ha/year	108 / **192** + 82 / **30** = 190 / **222**	141 / **159**	34 / **173**	98 / **259**	129 / **204**
	Direct CO_2 emissions* (diesel)	-	-	↘ fertiliser application: 30	↘ fertiliser application: 3	-
	Total direct + indirect emissions*	190 / **222** 142 to 282 / **170 to 315**	138 / **156** 94 to 214 / **107 to 236**	147 / **231**	101 / **262**	86 / **154** 0 to 129 / **47 to 204**
	Induced CO_2 and N_2O emissions (upstream)	109 78 to 156	76 52 to 118	87	55	65 0 to 98
	Total* $kgCO_2e$/ha/year	299 / **331**	214 / **232**	234 / **318**	156 / **317**	151 / **219**
Unitary cost	**Purchases** €/ha	management tool: 9.3 (€/10/ha x 93%)	additional cost of incorporation (B2): 1.5		inhibitor: 31.2 (€0.34/kgN)	fertiliser application equipment for seed drill: 2
	Savings €/ha/year	↘ fertiliser: -18 (-13.5 to -26.8)	↘ fertiliser: -13.1	↘ fertiliser: -13.7 -1 fertiliser application: -9	↘ fertiliser: -9.3 -0.95 fertiliser application: -6.1	↘ fertiliser: -11.2
	Total €/ha/year	**-8.7** (-4.1 to -17.5)	**-11.6** (-7.5 to 18.7)	**-22.7**	**15.8**	**-9.1** (2.1 to -14.7)
Potential applicability	**Theoretical potential applicability**	All fertilised arable crops + silage maize		Winter arable crops: 7.8 Mha	All arable crops excluding sunflowers and rice	Spring arable crops: 4 Mha
	Technical criteria	excluding sugar beet	excluding rice	surface areas with high residual N at the end of winter	inhibitor combined with 20% of the total N dose (or 1 year/ 5)	solid fertiliser at the time of sowing
	Max. Technical Pot. Applicability (MTPA)	11.7 Mha	12.0 Mha	1.8 Mha	2.3 Mha (320,000 tN/year)	3.7 Mha
Adoption scenario	**2010 reference situation**	7%	0%	7%	1.6%	10%
	Adoption scenario	Hypoth.: MTPA reached in 2022	Hypoth.: MTPA reached in 2028	Hypoth.: MTPA reached in 2022	Hypoth.: MTPA reached in 2022	Equipment required ➧ MTPA reached in 2030
						

* "CITEPA" calculation / **"expert" calculation**

Table 1

nitrogen applied by around 40 kgN/ha, i.e. 25% of the current average dose; on maize, combining A, B and C3 generates a reduction of around 36 kgN/ha, i.e. 23% of the current dose.

• Estimation of unitary abatement potential

The emissions abatement results from the effects of the sub-measures on: the total mineral nitrogen applied, losses due to leaching and volatilisation outside the field, upstream emissions related to the production and transport of synthetic fertilisers.

Two methods are used: the "CITEPA" calculations based on 1996 IPCC recommendations, and an "expert" calculation, which differs due to the use of:

- for direct emissions at field level, an exponential function, in line with the evolution of international knowledge, and set on the basis of French data presented in rank A publications;
- for indirect emissions due to volatilisation or leaching, new emission factor values (IPCC 2006), which have also been modified (based on the scientific literature) to take into account the effects of the sub-measures on these emissions;
- for direct and indirect emissions, coefficients taking into account the specific effects of the practices tested (localised application, use of inhibitors) derived from the scientific literature.

Target effect:

. **A reduction in direct and indirect N_2O emissions** related, depending on the sub-measures, to reducing the total amount of nitrogen fertilisers applied, reducing direct N_2O emissions per unit of nitrogen applied, or reducing losses due to leaching or volatilisation. The emissions are estimated using the two calculation methods indicated above.

Other effects quantified:

. **A reduction in direct CO_2 emissions due to the diesel consumption of agricultural machinery**, associated with modifying technical fertiliser application management techniques (elimination of one application, incorporation of fertiliser into the soil). These emissions are estimated on the basis of the Dia'terre® - Ges'tim database.

. **A reduction in induced emissions,** upstream of the farm, related to the production and transport of mineral nitrogen fertilisers and of fuels for agricultural machinery. These emissions are assessed on the basis of the Dia'terre® - Ges'tim database.

• Estimation of the unitary cost for the farmer

The cost (or saving) associated with a sub-measure includes:

- the cost of any specific equipment and/or inputs: acquisition of a fertiliser application management tool (such as Farmstar) for 93% of the surface areas (A), the additional cost of machinery for incorporation of organic waste (B2), or fertiliser application equipment for a seed drill (C3); the purchase of the nitrification inhibitor (such as DMPP; C2);
- synthetic nitrogen fertiliser savings;
- any reduction in the number of machine operations due to the elimination of one nitrogen application (C1 and C2).

• Estimation of the impact on a national scale

Maximum Technical Potential Applicability (MTPA)

Sub-measures A and B theoretically concern all land with fertilised annual crops (hence excluding legume crops). The only restriction considered is exclusion of sugar beet from the potential applicability of A.

However, sub-measures C only apply to certain situations: delaying the nitrogen application in the spring (C1) only concerns winter crops; the addition of nitrification inhibitor (C2) has a ceiling of 20% of possible maximum surface areas due to potential ecotoxicity; localised incorporation of fertiliser (C3) is only envisaged for spring crops.

Measure adoption scenario

For three of the sub-measures proposed (A, C1 and C2), involving technical adjustments, the hypothesis adopted is that the MTPA can be reached by 2022. For C3, which requires modification of spreading equipment, the dissemination adopted is slower.

The adoption of the sub-measures could be promoted by reinforcement of the "Nitrates directive" or an increase in fertiliser prices. The (ongoing) development of tools to aid in the assessment of organic sources (composition and quantity) and the introduction of a financial incentive are assumed to promote the adoption of B and C2, respectively.

IV- Results and their context

• The results

From the point of view of their potential abatement, the sub-measures examined are categorised as follows:

- with the "CITEPA" calculation, only taking into account the reduction in mineral nitrogen doses applied, the highest annual unitary abatement potentials are obtained by adjusting yield targets (A), then making better use of organic fertilisers (B) or performing localised incorporation of fertilisers (C3). The lowest abatement is that generated by delaying the first fertiliser application to cereals until a subsequent date(C1), since the nitrogen saving only consists of the difference in efficiency of the nitrogen between the two application dates;
- with the "expert" calculation, the abatement potentials are higher. The highest unitary abatement is obtained by adding nitrification inhibitor (C2); the values for the other sub-measures are fairly similar. All the sub-measures lead to comparable nitrogen application reductions (15 to 20 kgN/ha) and affect approximately the same processes.

The main differences between the sub-measures concern their potential applicability, large for A and B (which concern practically all arable crops), and more limited for the sub-measures related to nitrogen efficiency.

For all these sub-measures, the abatement potential related to the production and transport of nitrogen fertilisers is high, representing about 50% of the direct abatement.

To sum up, these sub-measures generate total abatements (including induced emissions) in the region of 0.15 to 0.30 tCO_2e/ha/year with the "CITEPA" calculation method, and 0.18 to 0.33 tCO_2e/ha/year with the "expert" calculation method. These values are close to those estimated in similar studies conducted abroad.

Four of the sub-measures have a "negative" cost, i.e. they represent a saving to the farmer. Sub-measure C2 is expensive due to the cost of nitrification inhibitor.

			Year 2030						Cumulative value over the period 2010-2030				
			A	B	C1*	C2*	C3	A+B+C1 +C2+C3 **	A	B	C1*	C2*	C3
Abatement potential ("CITEPA" method) Without induced emissions		$MtCO_2e$	2.2	1.7	0.3	0.2	0.3	**4.6**	32.4	22.3	3.9	3.3	3.8
Abatement potential ("expert" method)	Without induced emissions	$MtCO_2e$	2.6 2.0 to 3.7	1.9 1.3 to 2.8	0.4 0.1 to 0.7	0.6 0.3 to 0.8	0.6 0.2 to 0.8	**6.1** **3.9 to 8.8**	38 29 to 54	25 17 to 38	6 2 to 10	9 4 to 11	7 2 to 9
	With induced emissions		3.9 3.3 to 5.0	2.8 2.2 to 3.8	0.6 0.3 to 0.8	0.7 0.4 to 0.9	0.8 0.4 to 1.0	**8.8** **6.6 to 11.5**	56 48 to 72	37 30 to 50	8 4 to 12	10 6 to 13	10 5 to 12
Total cost for farmers		€M	-101 -205 to -49	-140 -226 to -90	-41 -68 to -12	37 18 to 46	-34 -55 to 8	**-280** **-536 to -97**	-1476 -2,977 to -706	-1869 -3,024 to -1,200	-596 -993 to -178	520 260 to 650	-397 -641 to 92
Cost per metric ton of CO_2e for the farmer ("expert" methods, without induced emissions)		€/tCO_2e	-39 -56 to -24	-74 -80 to -70	-98	60	-59 -72 to 45	**-46** **-58 to -32**	-	-	-	-	-

M: million
* the ranges (abatement, cost) concern the potential applicability reached in 2030
** values obtained by adding A+B+C1+C2+C3, without taking into account interactions between sub-measures.

Table 2

Abatement potential and costs for the measure as a whole

Assuming the sub-measures to be additive, the overall abatement calculated in 2030 for all 5 sub-measures is 6.1 $MtCO_2e$ ("expert" calculation, excluding induced emissions).

However, the assumption that the sub-measures are additive is simplistic since the implementation of one sub-measure reduces the amount of mineral nitrogen applied, and hence the potential applicability to which the other sub-measures could apply. The estimation for the measure as a whole was re-calculated, successively applying the sub-measures, in a defined order (A then B then C1 to C3) to the scopes concerned, taking into account interactions between the sub-measures. This calculation taking into account interactions leads to an abatement in 2030 of 5.3 $MtCO_2e$ ("expert" calculation, excluding induced emissions). Taking into account interactions slightly modifies the unitary cost of the sub-measures in some cases and leads to a cost on the MTPA in 2030 of - €290 M (compared to - €280 M for the sum of the costs of the sub-measures).

• The sensitivity of the results to the hypotheses

The unitary abatement is primarily affected by the hypotheses concerning the effects of practices on the reduction of the amounts of mineral nitrogen applied, reflected by: estimation of the rate reduction resulting from the measure, or a volatilisation coefficient (management of organic products, localised incorporation of nitrogen, nitrification delayed by an inhibitor), or a fertiliser equivalence coefficient (Keq) for sub-measure B. Thus, for example, a 10% increase in the value of this coefficient used to convert the quantities of nitrogen supplied by organic products into the amount of nitrogen used by a crop increases the unitary abatement by approximately 13%.

The results are slightly affected by the statistical data used, which date from 2006 (last available survey) for cropping practices. Yet practices have evolved since then, particularly with the progressive adoption of rational fertiliser application principles. These changes mainly affect the potential applicability to which the sub-measures apply.

Finally, the potential for adoption of certain sub-measures by farmers (the use of nitrification inhibitor, localised incorporation of fertiliser) is relatively uncertain, in the absence of an incentive or financial taxation scenario. The cumulative abatement in 2030 is therefore highly sensitive to the dissemination hypotheses adopted.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effects

The use of an "expert" calculation, incorporating the 2006 IPCC coefficients and taking into account the known effects of practices on direct and indirect emissions, slightly increases the estimation of the potential abatement for sub-measures A and B, for which only the effect of the amount of fertiliser nitrogen applied on the emissions is modified by the calculation. The increase in the abatement is much greater for sub-measures C1 to C3, for which the "CITEPA" calculation does not take into account changes linked to the improved efficiency of fertilisers.

From the point of view of inventories, the current calculation method (1996 IPCC), which only takes into account the quantities of nitrogen applied to calculate emissions, does not adequately incorporate the effects of practices that are very interesting for abatements (such as the use of nitrification inhibitors or the localised incorporation of nitrogen in the soil). The exponential relationship introduced in this study is based on an analysis of French publications. It follows on from recent international publications highlighting this form of relationship, which may be proposed to the IPCC. Following consolidation of knowledge, the next step might be to take into account the variability of N_2O emissions on the basis of soil and climate conditions.

Verifiability of implementation of the measure

The evolution of mineral fertiliser deliveries (statistics published by the UNIFA - French Fertiliser Manufacturers' Union) could be used by the CITEPA to quantify the sub-measures implemented. The "Nitrates" directive (91/676/EEC), the cross-compliance of CAP aids, the French "Installations Classées pour la Protection de l'Environnement" (ICPE - "Classified Facilities for Environmental Protection") system and Agro-Environmental Measures are all mechanisms requiring farms to hold a Provisional Fertiliser Plan and Fertiliser Application Records that can be monitored for implementation on the ground. However, the technical application methods (dates, incorporation in the soil, etc.) are difficult to verify.

• The contexts and measures liable to promote the roll-out of the measure

For all the sub-measures - and particularly those requiring very few new technical elements (adjustment of application rates in line with yield targets, delay in application date, etc.) - an increase in fertiliser prices and/or financial measures aimed at reducing the agricultural sector's reliance on synthetic nitrogen fertilisers could accelerate the adoption of the measure.

The adoption of certain techniques could be made easier by improvements to decision-making tools (DMTs) for the management of nitrogen and their more extensive use.

• Other effects of the measure

The sub-measures proposed lead to a reduction in the amount of synthetic mineral fertilisers used on crops and, consequently, to a potential reduction in surplus nitrogen fertiliser application. They therefore fit squarely with public policies implemented within the French national measure programme to protect water from pollution by nitrates of agricultural origin, based on the "Nitrates" directive. Some of the sub-measures also contribute to the objective of reducing air pollution due to ammonia volatilisation.

Finally, reducing mineral nitrogen consumption also offers benefits in terms of trade balance, since France imports 60% of the synthetic fertiliser that it uses, and almost all the raw materials for the remaining 40%.

• Conclusions

The potential of reducing mineral fertiliser application without affecting yields is high and the majority of the sub-measures are "win-win" since reducing fertiliser applications also reduces costs for farmers. This effect is liable to be amplified by the rise in mineral fertilisers prices resulting from the expected increase in energy costs. There is therefore considerable room for progress without affecting yields.

The abatement potential associated with reducing the application of mineral fertilisers to crops is under-estimated here since the calculations do not take into account legume crops and grassland (covered by Measures 2 and 6), or vegetable, market garden and industrial crops, or perennial crops (vines and orchards). The abatement potential linked to an increase in organic agriculture surface areas is not considered either (the new organic agriculture development plan aims to double surface areas by 2017); since the arable surface areas concerned are limited (1.6% in 2011), their extension would have little impact in terms of potential GHG abatement.

Managing nitrogen fertiliser application for arable crops is technically complex because it needs to take into account the diversity of soil and climate conditions and uncertainties related to weather, the biological function of soils and stocking, as well as the availability of nitrogen forms. These uncertainties often lead farmers to seek to minimise the risks of yield losses by increasing nitrogen application rates. Practices aimed at reducing the risks of losses (via ammonia volatilisation, in particular) should therefore be given priority. This analysis also demonstrates that approaches promoting the abatement of GHGs are also favourable in terms of limiting the nitrate contamination of surface and ground water. This assumes that practices that have as yet been little examined and/or practised (the localised application of fertilisers in the soil or the use of nitrification inhibitors, for example) be the subject of more systematic studies in France in order to pave the way for providing farmers with support. There is also considerable room for progress in terms of the implementation of nitrogen fertiliser application management tools - still little used - with these having demonstrated their value to help reduce the total amount of nitrogen applied whenever yield targets are over-estimated.

2 Increase the proportion of legumes in arable crops and temporary grassland, in order to reduce N_2O emissions

↘ N_2O

A. Increase the surface areas of grain legumes on arable farms
B. Increase and maintain legumes in temporary grassland

I- Challenge and principle of the measure

N_2O emissions from agriculture resulting from nitrogen fertiliser application can be reduced by a more rational and efficient use of fertilisers (Measure 1) but also by introducing legumes into crop rotations and grassland. Since they symbiotically fix nitrogen from the air, these crops do not actually require the addition of any nitrogen fertilisers. In addition, the nitrogen that they supply to the soil also means that the amount of fertiliser applied to the next crop can be reduced.

The measure is designed to increase the proportion of grain legumes in arable systems and the proportion of fodder legumes in temporary grassland The introduction of grain legumes in arable systems significantly modifies crop rotations and hence cropping plans and agricultural outputs on a national scale; substituting crops on grassland does not have these effects.

II- Mechanisms and technical methods of the measure

• Effects of legumes on N_2O emissions

N_2O emissions from the soil, resulting from nitrification and denitrification processes, appear to be very closely linked to the amount of nitrogen supplied to crops. They are therefore calculated by applying "emission factors" (expressed in %) to these fertiliser applications.

The main expected effect of legumes is a fall in N_2O emissions resulting from a reduction in mineral fertiliser requirements. But their balance also depends on the effects of the nitrogen they fix and return to the soil, which may also constitute a source of N_2O emissions.

Hence, until recently, symbiotic fixation was considered to be a source of N_2O emissions, in the same way as mineral fertiliser application (the same emission factor was applied to the nitrogen fixed by the legume; Table 1). N_2O emissions from legume crops have proved to be highly variable, but significantly lower, on average, than those measured in fertilised crops. These observations led the IPCC to revise its calculation rules in 2006 and to recommend that symbiotic fixation no longer be considered as a source of emissions. However, the 2006 rules have not yet been applied in the 2010 national inventory.

N_2O emissions linked to the decomposition of legume crop residues are difficult to quantify: they are highly variable and depend, in particular, on the residue incorporation methods used, and on soil and climate conditions during decomposition. These residues, which have high N contents but represent low levels of biomass, leave nitrogen quantities in the soil close to those of other crops. Since the emission factor of residues is identical between crops, estimated emissions from residues are no higher than for other crops, as demonstrated by recent data.

Finally, in certain conditions, legume crops can constitute N_2O sinks. For example, recent French research has demonstrated an N_2O consumption equivalent to 75 gN_2O/ha during the growing cycle for a soybean crop. However, although this effect is observed in controlled conditions, it is not demonstrated *in situ* or for all the grain legumes that can be grown in France (in particular, peas). It will not therefore be taken into account in this study.

• Other effects of legumes

Since grain legumes leave few residues in the soil (making soil preparation easier before sowing), the crops that follow are usually sown using no-till methods (see 2006 "Cropping Practices" survey); thus the reduction in emissions related to the change of soil tillage after legume crops will also be taken into account.

Replacing gramineous grasslands with legume grasslands (pure or intercropped with a gramineous) changes the composition of livestock's diet and has consequences on methane emissions from ruminants; these effects will not be quantified here.

• The sub-measures studied

In arable systems, the objective is to introduce more grain legume crops, in place of other annual arable crops. This sub-measure therefore modifies cropping plans and crop rotations, as well as the crop management applied on the non-legume crops, depending on the legume crop.

On grassland, the aim is to increase the proportion of legumes in temporary grassland rotations (by partially or totally replacing gramineous crops) and, in the case of mixed crops, to maintain legumes throughout the lifetime of the grassland, limiting nitrogen fertiliser application to prevent the gramineous from competing too strongly with the legume.

Nitrogen source	IPCC 1996	IPCC 2006
Mineral nitrogen	1.25%	1.00%
Symbiotic fixation	1.25%	0
Residues of legumes and other crops	1.25%	1.25%

Table 1. Direct N_2O emissions: evolution in emission factors

III- Calculations of the abatement potential and cost of the measures

• Calculation methods and systems adopted

Introducing legumes modifies the surface areas of other arable crops and hence their GHG emissions. The calculations were therefore made directly on a France-wide scale (and not on the basis of additional legume hectares) in order to be able to incorporate the effects of these changes in cropping plans. Values per hectare of legume crop sown were then calculated on the basis of these national values.

The **crop substitutions** following the introduction of grain legumes are difficult to anticipate. Several hypotheses were explored (see section IV), the most realistic of which was used for the calculations: 2/3 of the legume crops introduced will replace barley (less profitable than wheat and oilseed rape), 1/6 of them will replace wheat and 1/6 will replace oilseed rape.

The **reductions in nitrogen fertiliser application** resulting from the growing of legume crops are estimated using the following hypotheses: absence of fertiliser application to grain legumes and a 33 kgN/ha reduction in fertilisers on the next crop; a 35 kgN/ha reduction in fertiliser applications to mixed grassland including less than 20% legumes and a 14 kgN/ha reduction for mixed grassland with between 20 and 40% legumes.

The data for the surface areas of the various crops and grasslands are taken from the 2010 Annual farming statistics (SAA) database.

• Effects of the measure on GHGs and calculation of its unitary abatement potential

For all the direct and indirect emissions, the calculations are made using the emission factors defined by the IPCC in 1996 and used in the 2010 national emissions inventory ("CITEPA" method), then with the new parameters adopted by the IPCC in 2006 ("expert" method).

Target effect:

. **A reduction in N_2O emissions** (direct and indirect) **linked to mineral fertiliser application**. The abatement results from the elimination of nitrogen applications to the legume and their reduction on the next crop.
The direct emissions are estimated using the emission factors in Table 1. The indirect emissions, resulting from nitrate leaching and ammonia volatilisation from the fertilisers applied, are once again calculated using the emission factors defined by the IPCC in 1996, and revised (for leaching) in 2006.

Other effects quantified:

. **Direct N_2O emissions linked to the legume**, i.e. to symbiotic nitrogen fixation, and to the decomposition of legume residues for the crops sub-measure.
The calculations use 1996 and 2006 IPCC emission factors (Table 1), concerning symbiotic fixation (initially considered to emit as much as fertiliser application, then not to be a source of emissions) and crop residues (quantification of which has not changed).

. **The reduction in direct CO_2 emissions** due to fuel consumption on the farm. The diesel savings resulting from changes in crop rotations and crop management: fewer tractor operations to apply fertiliser and plant health products (because the number varies depending on the crop grown and the previous crop), possible elimination of tillage before the crops following the grain legumes. The fuel consumption values are calculated using the technical references of the 2010 Centre – Ile-de-France region mutual aid scale, and the emissions calculated using CITEPA emission factors.

. **Induced CO_2 emissions** linked to the production and transport of inputs upstream of the farm (mineral nitrogen fertilisers, plant health products and fuel). The emission factors used are those used in the Dia'terre® - Ges'tim database.

• Estimation of the unitary cost for the farmer

Crops:

The technical costs for the farmer include:

- savings in fertilisers (application) and plant health products, as well as those resulting from the elimination of tillage following the legume crop;
- gross margin increases achieved for the next crop. These increases - which can be calculated on a national scale - are not independent of the cropping plan changes induced by introducing a greater surface area of grain legumes. Consequently, the benefit/economic cost related to these two effects was calculated globally.

Grassland:

The only "costs" correspond to reduced fertiliser application (savings in fertiliser and application operations); yield is not affected by modifying the composition of the grassland.

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

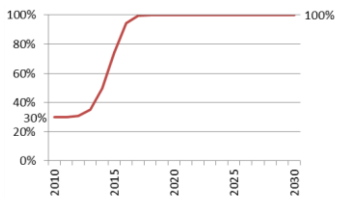
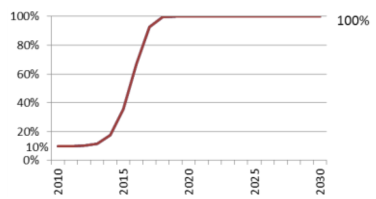
In **arable systems**, the surface areas are limited by:
- the need to avoid stony soils, where the harvesting of certain legume crops - which requires scraping the ground with the cutter bar - damages the combine harvester;
- the inability to plant legumes in soils with a water reserve of less than 80 mm, since they are highly sensitive to water stress;
- a maximum return time in the same field of 6 years for legumes (to reduce the risk of *Aphanomyces euteiches* development, a root disease that permanently prevents the cultivation of peas in infested soil).

On **grassland**, no technical restrictions limit the potential applicability.

Measure adoption scenario

In 2010, the surface areas for grain legumes and temporary grassland including over 40% legumes accounted for approximately 16% of the MTPA.

In **arable systems**, the hypothesis adopted is rapid dissemination. On **grassland**, it is assumed that the introduction of legumes will be slower given the renewal time of these permanent crops.

	Sub-measures	A. Grain legumes in arable systems	B. Legumes on grassland
Technical content	**Introduction of legumes**	Introduction of a grain legume in place of wheat (1/6 of legume surface areas), barley (2/3) and oilseed rape (1/6) → new cropping plan in France	Increase and maintain the proportion of legumes in temporary grassland.
	Reduction in fertiliser application	Elimination on the legume crop, 33 kgN/ha reduction on the next crop → fertiliser saving on a France-wide scale: 155 640 tN.	35 kgN/ha reduction on grassland with less than 20% legumes and 14 kgN/ha reduction on grassland with between 20 and 40% legumes (i.e. -29 kgN/ha on average) → fertiliser saving on a France-wide scale: 82 980 tN
Abatement potential	**N_2O emissions*** (direct and indirect) **linked to mineral fertilisers**	France total: 1.5 / **0.97** MtCO$_2$e/year Per ha of legume introduced: 1,706 / **1,100** kgCO$_2$e/year	France total: 0.80 / **0.48** MtCO$_2$e/year Per ha of grassland (<40% legumes): 283 / **170** kgCO$_2$e/year
	N_2O emissions* (direct) **linked to the legume**	France total: -1.05 / **-0.07** MtCO$_2$e/year Per ha of legume introduced: -1 191 / **-77** kgCO$_2$e/year	France total: 0 / **0** MtCO$_2$e/year Per ha of grassland: 0 / **0** kgCO$_2$e/year
	Direct CO_2 emissions* (diesel)	France total: 0.02 / **0.02** MtCO$_2$e/year Per ha of legume introduced: 21 / **21** kgCO$_2$e/year	France total: 0.004 / **0.004** MtCO$_2$e/year Per ha of grassland: 1.36 / **1.36** kgCO$_2$e/year
	Total direct + indirect emissions*	France total: 0.47 / **0.92** MtCO$_2$e/year Per ha of legume introduced: 636 / **1 044** kgCO$_2$e/year	France total: 0.80 / **0.48** MtCO$_2$e/year Per ha of legume introduced: 284 / **171** kgCO$_2$e/year
	InducedCO_2 emissions (upstream)	France total: 0.83 MtCO$_2$e/year Per ha of legume: 947 kgCO$_2$e/year	France total: 0.44 MtCO$_2$e/year Per ha of grassland: 156 kgCO$_2$e/year
	Total MtCO$_2$e/year (France) kgCO$_2$e/ha/year	France total: 1.30 / **1.75** Per ha of legume: 1,583 / **1,991**	France total: 1.24 / **0.92** Per ha of grassland: 440 / **326**
Cost	**Input savings** (France)	Fertiliser spreading operation savings Elimination of tillage on 396 187 ha: -€20.77 M	Fertiliser + fertiliser spreading operation savings: €88.9 M
	Gross margin increase for the next crop	France total: €52.32 M Per ha of ACOP: €4.40 Per ha of legume introduced: €60	-
	Total €/year (France) €/ha/year	France total: 16,991,900 Per ha of ACOP: 1.43 Per ha of legume introduced: 19.36	France total: -88,903,600 Per ha of grassland (<40% legumes): -31.50
Potential applicability	**Theoretical potential applicability**	All arable crops: 12,515,200 ha	All temporary grassland: 3,143,100 ha
	Technical criteria	Exclusion of very stony soils and/or those with a low UR (< 80 mm) Return frequency of legumes limited to 1year in 6: i.e. 1/6 of surface areas each year	No technical restrictions
	Max. Technical Pot. Applicability (MTPA)	1,274,900 ha	3,143,100 ha
Adoption scenario	**2010 reference situation**	Grain legume surface areas: 397,100 ha (i.e. 31.1% of the MTPA)	Temporary grassland with > 40% of legumes: 320,600 ha (including 84,586 ha of alfalfa for drying) (i.e. 10.2% of the MTPA)
	Adoption scenario	MTPA reached by 2017 	MTPA reached by 2021 

* "CITEPA" method/ **"expert" method**

Table 2

IV- Results and their context

		units (M: million)	Year 2030			Cumulative value over the period 2010-2030	
			Crops	Grassland	**Total 2 sub-measures**	Crops	Grassland
Abatement potential ("CITEPA" method) Without induced emissions		*$MtCO_2e$*	0.5 (0.2 to 0.8)	0.8 (0.7 to 1.7)	**1.3** **(0.9 to 2.4)**	7.6 (2.7 to 12.5)	11.6 (10.2 to 24.0)
Abatement potential ("expert" method)	Without induced emissions	*$MtCO_2e$*	0.9 (0.3 to 1.4)	0.5 (0.4 to 1.0)	**1.4** **(0.7 to 2.4)**	14.7 (5.3 to 23.3)	7.0 (6.1 to 14.4)
	With induced emissions	*$MtCO_2e$*	1.7 (0.6 to 2.7)	0.9 (0.8 to 1.9)	**2.7** **(1.4 to 4.6)**	28.2 (10.0 to 43.4)	13.3 (11.7 to 27.6)
Total cost for farmers (without private transaction costs)		*€M*	17 (6 to 26)	-89 (-168 to -73)	**-72** **(-163 to -47)**	274 (98 to 415)	-1,289 (-2,444 to -1,150)
Cost per metric ton of CO_2e for the farmer ("expert" method, without induced emissions)		*€/tCO_2e*	19 (18 to 19)	-185 (-189 to -169)	**-52**	-	-

Table 3

• The results

Crops:
The abatement per ha of legume planted was estimated to be 636 kgCO_2e/ha/year (1,040 kgCO_2e/ha/year with the "expert" method) for direct and indirect emissions related to the farm, and 947 kg CO_2e/ha/year for emissions induced upstream.

Applying this abatement to the maximum technical potential applicability, the annual abatement is 0.5 kgCO_2e/ha/year (0.9 MtCO_2e/year with the "expert" method) for direct and indirect emissions related to the farm, and 0.8 MtCO_2e/year for emissions induced upstream.
The cumulative abatement for the period 2010-2030 is estimated to be 7.6 MtCO_2e ("CITEPA" method) and 14.7 MtCO_2e ("expert" method) for direct and indirect emissions related to the farm, and 13.4 MtCO_2e for induced emissions upstream.
The cost per metric ton avoided is estimated to be €19/tCO_2e.

Grassland:
The unitary abatement was estimated to be 284 kgCO_2e/ha/year (171 kgCO2e/ha/year with the "expert" method) for direct and indirect emissions related to the farm, and 156 kg CO_2e/ha/year for emissions induced upstream.
Applying this abatement to the MTPA, the annual abatement is 0.8 MtCO_2e/year (0.5 MtCO2e/year with the "expert" method) for direct and indirect emissions related to the farm, and 0.4 MtCO2e/year for emissions induced upstream.
The cumulative abatement for the period 2010-2030 is estimated to be 11.6 MtCO_2e ("CITEPA" method) and 7.0 MtCO_2e ("expert" method) for direct and indirect emissions related to the farm, and 6.4 MtCO_2e for induced emissions upstream.
The cost per metric ton of CO_2e avoided is estimated to be €185/tCO_2e and therefore constitutes a gain.

Comparison with the results of other "GHG abatement" studies performed around the world shows that the unitary abatements calculated here are within the lower range of estimates for grassland, and in the middle range for grain legumes. The estimated increase in grain legume surface areas (4.5% of arable land) is low compared to the level of legumes in some countries (13% of arable land in Canada, 32% in the USA). Similarly, a significant increase in surface areas of temporary grassland based on fodder legumes may appear to be an interesting and effective option to reduce GHG emissions in France, but it would be outside the scope of the study since it would modify agricultural systems too much.

• The sensitivity of the results to the hypotheses

The sensitivity to **calculation rules** - particularly the emission factor allocated to symbiotic fixation - is very high (value almost doubling).

The sensitivity of the results to the hypotheses used for **crop substitutions** was tested: depending on the hypotheses used (replacement in different proportions of oilseed rape, barley and wheat), the emissions are also variable (from 0.82 to 0.91 MtCO_2e/year), and the costs even more so (from -€19/tCO_2e to €77/tCO_2e). However it is difficult to predict which substitutions would actually be made, since these would depend on relative prices between crops and consequences related to use in animal nutrition, particularly for barley.

The hypotheses for calculation of the maximum technical potential applicability and the unitary abatement also have a significant impact on the final calculations. The lower and upper ranges calculated in this way vary from 0.33 to 1.44 MtCO_2e/year (with the "expert" method), with, however, costs that are very stable per ha of legume introduced or per metric ton of CO_2e avoided.

For grassland, the sensitivity of the calculations is primarily related to the hypotheses relating to MTPA and nitrogen fertiliser application reduction calculations, causing the emissions to vary between 0.42 and 1.0 MtCO_2e/year, the gain between €31 and €60 per ha of grassland concerned, and that per metric ton of CO_2e avoided between €169 and €189.

The estimated costs are also sensitive to variations in the **prices** of inputs and products harvested, with the margins used being those for 2010.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effect

Up until 2006, emissions calculations using the official IPCC method considered symbiotic fixation to be a potential source of N_2O emissions in the same way as nitrogen fertiliser applied to crops. The latest IPCC recommendations in 2006 took into account evolving knowledge and recommend that symbiotic nitrogen fixation no longer be included when calculating N_2O emissions.

Verifiability of implementation

As regards the introduction of grain legumes, the implementation of practices could be estimated using annual farming statistics and the "Cropping practices" survey (surface areas, fertiliser doses applied, etc.), but also using aid declarations (CAP) concerning crop surface areas. However, the introduction of legumes in grassland is difficult to calculate, particularly for mixtures, and could require *in situ* observations.

• The contexts and measures liable to promote the roll-out of the measure

Grain legume surface areas have varied significantly over time: very low in the early 1970s, they peaked in 1993, exceeding 720,000 ha, before falling again to a low of approximately 203,000 ha in 2009. These fluctuations appear to be related to the following factors: firstly, variations in the prices of other raw materials (wheat and soybean cake) competing with protein crops for the production of cattle feed, and price ratios between the various arable crops; since the 1992 CAP, on a more occasional basis, intermittent crop aids; to a lesser extent, the expansion of *Aphanomyces* (promoted by not adhering to crop return times on the same field and by unfavourable soil moisture conditions), and the high sensitivity of these crops to abiotic stresses.

In addition, this high level of variability in their yields is not always clearly explained by farmers or their advisers. As a result, it is not always possible to make progress in terms of the management of this crop and producers are discouraged. It would probably be necessary to envisage providing better training for technicians (from Chambers of Agriculture and cooperatives), who often know little about these crops due to their low surface areas.

Beyond these technical and economic factors, a number of other factors, affecting all stakeholders involved in the supply chain, converge to limit the value of grain legume crops to farmers, cooperatives and the supply chain as a whole. A recent study[1] highlighted the importance of outlets, particularly in the animal nutrition sector: livestock feed manufacturers are willing to use peas as a raw material as long as the volumes available are very high and grouped together close to feed production plants, which is not the case today, due to low and geographically dispersed production.

Grain legumes were given public support in 2010, leading to a small increase in surface areas (from 203,000 ha in 2009 to 397,000 ha in 2010, before falling again to 278,000 ha in 2011). In addition, a sharp rise in synthetic nitrogen fertiliser prices tends to be favourable to legume crops. However, the unpredictable and unsustainable nature of these supportive measures or effects is unfavourable to maintenance of these crop areas. It should be noted that a "Plant Protein" Plan was announced at the start of 2013.

Increasing the proportion of legumes on **temporary grassland** does not pose the same difficulties. It requires, above all, a change in the habits of farmers (and probably in the advice provided to them). Managing gramineous grassland with synthetic inputs is easier and less risky than managing the balance between two plant species within the same grassland. Nonetheless, the elimination of nitrogen application should save time in terms of labour. However, the more variable composition of the fodder will probably require more careful management of the food supplements given to livestock. Such practices already exist and could be developed.

• Vulnerability and adaptability of the measure to climate change

Since grain legumes are particularly sensitive to abiotic stresses, climate change could induce a reduction in their productivity and an increase in their instability, with negative consequences on cultivated surface areas, the potential abatement and the estimated costs.

Conversely, the risk of a shortage of water for irrigation could lead to a reduction in surface areas of summer crops - highly water-dependent - in favour of less greedy crops, including legumes.

• Other effects of the measure

In the majority of French regions, the inclusion of legumes in rotations has a beneficial environmental impact in terms of the use of plant health products on a crop rotation scale, the use of water (in comparison to other summer crops), fossil fuel consumption, and biodiversity. The addition of a new crop to the cropping plan is generally favourable to a spreading-out of labour - something that is appreciated by producers - and should therefore be a favourable factor for the development of these crops.

• Conclusions

One specific characteristic of this measure is that it involves modifying rotations; this is a significant change that requires the adoption of strong hypotheses regarding crop substitutions, with potentially marked repercussions on production systems, and barely within the scope of this study. For grain legumes, it would involve a 3-fold increase in surface areas compared to their 2010 level; for fodder legumes, it would involve modifying grassland management and compositions on almost 90% of current surface areas.

On the basis of the calculations made, it appears that increasing the surface area of grain legumes in arable systems and increasing the proportion of fodder legumes on temporary cultivated grassland constitute significant levers for reducing GHG emissions, with an economic benefit (or a relatively low cost). The abatement potential calculated would be even greater if an increase in fodder legume surface areas was envisaged, something that was not done as part of this study since it would assume associated adaptations to animal nutrition systems and hence major modifications in production systems. The economic benefits were primarily obtained via a modification in nitrogen fertilisation practices. The economic benefits are also related to the incorporation of the previous crop "carry-over" effects of legumes in the management and calculation of subsequent crop performances, effects that have rarely been counted in economic studies to date and remain under-valued by practitioners. These elements suggest that the changes envisaged can only be achieved by means of strong and lasting political incentives and significant changes at various levels of the supply chain.

[1] Meynard et al., 2013. *Crop diversification: obstacles and levers Study of farms and supply chains*. Synopsis of the study report, INRA

3 Develop no-till cropping systems to store carbon in soils

↘ CO_2

A. Switch to continuous direct seeding
B. Switch to occasional tillage, 1 year in 5
C. Switch to continuous superficial tillage

I- Challenge and principle of the measure

The GHG balance of agriculture can be improved by increasing carbon storage in the soil in the form of organic matter, i.e. from CO_2 absorbed by plants. This storage can be increased by returning more organic matter to the soil (see Measure 4), but also by farming practices that delay their mineralisation and hence increase their storage time in the soil. No-till cropping practices are reputed to have this effect. By eliminating an operation requiring a high traction force, the approach also leads to fossil fuel savings. But it is also liable to increase N_2O emissions, which depend on the physicochemical conditions of the soil.

Since conventional tillage is defined by the fact that it turns over the soil (“full inversion tillage”), "no-till cropping practices" include all practices that do not involve turning over the soil. However, these practices are extremely diverse - ranging from minimum tillage of the soil to various depths to direct seeding or drilling - and will have different impacts. These practices mainly concern arable land, which will be the only areas considered here.

II- Mechanisms and technical methods of the measure

Among the various forms of no-till cropping practices, direct seeding (which only involves disturbing the soil along the seed line, to a depth of a few cm; NT) is the method focused on by the great majority of scientific studies to date, but remains little practised in France. Superficial tillage (ST) (to less than 15 cm depth) and occasional tillage (OT) are much more widespread. However, there is little information concerning these practices in the literature. Few agronomic trials have focused on these questions in France, where there is only one system of this type, set up more than 20 years ago (the Arvalis long term trial in Boigneville, south of Paris.

• The effects of no-till cropping practices on the soil and their emissions

Increase in carbon storage in soil

The absence of tillage or ploughing may increase C storage as a result of less mineralisation of organic matter, due primarily to its better physical protection in soil aggregates (which are not destroyed by tillage nor exposed to rain when the soil is bare) and to colder and moister conditions in the soil's surface layer.

Most available data come from comparisons between direct seeding and conventional tillage performed in North America, and some contain methodological biases: the additional storage of C may have been over-estimated, for example, by measurements limited to the upper soil layers or carried out over excessively short periods of time. Direct seeding leads to a significant stratification effect for organic matter present in the soil: the surface horizons (0-20 cm) store C, whereas the deeper horizons lose it. In addition, the storage kinetics are not linear: they are more rapid in the first few years and level out after a few decades

Recent methodologically reliable studies and meta-analyses have demonstrated nil or slightly positive balances, leading to a radical downwards reassessment of the C storage potential of direct seeding. We estimated effects of occasional tillage - little studied - by simulations. The few studies on superficial tillage did not show any difference in carbon stocks compared to conventional tillage.

Increase in N_2O emissions from the soil

The absence of tillage may increase N_2O emissions by promoting denitrification due to a more compact soil structure and an often higher moisture content, hence more anoxic conditions.

Many of the references available are based on discontinuous measurements of N_2O emissions, extrapolated over the year. The estimates used here are only based on studies involving continuous N_2O emissions measurements, which are more reliable and more accurate. No-till often lead to higher N_2O emissions - but only slightly - than tillage, except in the case of poorly drained soils; however the variability in emissions is significant.

The bibliographic analysis leads to the following values being used.

Additional C storage / continuous tillage	
Direct seeding	0.15 tC/ha/year (0 to 0.3)
Occasional tillage 1 year in 2 1 year in 5	0.05 tC/ha/year 0.10 tC/ha/year
Superficial tillage	0
Additional N_2O storage / continuous tillage	
Direct seeding, well aerated soil Poorly drained soil	0.15 kgN/ha/year (0 to 0.3) 2 kgN/ha/year
Superficial tillage	0

Table 1. Emission and storage values in the literature

The information available does not demonstrate any variation in additional C storage or N_2O emissions with no-till as a function of climate or crop.

Other emissions from the soil

CH_4 emissions appear to be negligible compared to other GHGs (CO_2 and N_2O); in addition, they are little influenced by tillage practices.

• Other effects of no-till cropping systems

A number of other effects of no-till cropping practices could have an impact on their GHG balance and their cost for the farmer:

- the resulting fuel and labour time savings (reduction in CO_2 emissions and benefit for the farmer);
- the increased use of herbicides, as weeds are no longer controlled by tillage (emissions and costs associated with the production and application of the product);
- the reduced yields observed with no-till farming (loss of income);
- erosion prevention, which would reduce organic matter losses. However, displacement of C as a result of erosion does not necessarily lead to additional CO_2 emissions on a watershed scale.

• The three technical options studied

These options relate to a switch in previously conventionally tilled fields to:

- continuous direct seeding (NT),
- occasional tillage one year in 5 (OT1/5), alternating with years of direct seeding,
- superficial tillage of the soil to a depth of around ten centimetres (ST*)*.

These 3 options cannot be added together since they are alternative solutions concerning the same surface areas.

III- Calculations of the abatement potential and cost of the measures

• Systems and calculation methods used

The analysis of practices is based on the results of the last available "Cropping practices" (CP) French survey - from 2006 - and on a multi-body study focusing on no-till cropping practices[6]. The crop surface areas are taken from the 2010 Annual farming statistics (SAA) database.

The **2010 reference situation** is estimated on the basis of the 2006 "Cropping practices" data, "updated" by applying the no-till growth rate observed in recent years of +2% of annual crop surface areas per year. i.e. for 2010: 58% of surface areas undergoing continuous tillage, 41% undergoing tillage one year in two (alternating with superficial tillage, an option known as T-ST1/2) and 1% with direct seeding.

The calculations were made for the 3 options (DS, OT1/5 and ST) and for T-ST1/2 (option for the 2010 situation). Given the uncertainties relative to the variables, the calculations include a mean value, as well as lower and upper values ("range").

According to the 2006 "Cropping practices" survey, no-till farming is accompanied by the increased use of herbicides, with +0.3 applications per year, all crops combined.

• Estimation of unitary abatement potential

Target effect:

. Additional C storage in the soil. This is not taken into account by the CITEPA calculation method for the 2010 emissions ("CITEPA" method), and hence not currently counted in the national inventory. An "expert" calculation method is proposed here, based on the scientific literature using the values in Table 1.

Other effects quantified:

. The reduction in direct CO_2 emissions associated with fuel savings. This saving is calculated using data concerning diesel consumption for the various farming operations.

. The increase in N_2O emissions. This is calculated with the value selected for aerated soil (Table 1), since poorly drained soils are excluded from the scope of application of the measure.

. Induced emissions (occurring upstream of the farm) associated with the production and transport of inputs. The variation in these emissions, due to lower fuel consumption, on the one hand, and additional herbicide use, on the other, is quantified.

• Estimation of the unitary cost for the farmer

This technical cost (calculated with 2010 prices) takes into account the following:

- the savings in fuel (falling, for a wheat-maize rotation, from 94 litres using tillage to 54 l using DS) and labour time related to the elimination of tillage;
- the potential reduction in yields, which, assuming a high cost hypothesis, is -1% with ST, and -5.2% with DS. Assuming a low cost hypothesis, this reduction is nil;
- the increase in herbicide use (product purchase and application cost).

Once established, the value of equipment does not differ between farms using tillage and those using direct seeding. However, switching to direct seeding requires the use of a specific seed drill: its purchase can be counted in the DS adoption costs (additional investment) or considered to be part of normal equipment renewal.

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

The MTPA is estimated by subtracting the surface areas for crops not suitable for no-till cropping practices (root crops; monocropping for which weed control is more difficult) and soils where no-till methods are not very appropriate and induce incompatible N_2O emissions (poorly drained soils) from the total cultivated crop surface area.

Measure adoption scenario

Given the strong growth of no-till cropping practices in France in the past ten years, the hypothesis applied for each of the options is an adoption for the entire MTPA by 2030.

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[6] Labreuche J., Le Souder C., Castillon P., Ouvry J.F., Real B., Germon J.C., de Tourdonnet S., 2007. Evaluation des impacts environnementaux des Techniques Culturales Sans Labour (TCSL) en France. ADEME contract report, 400 p.

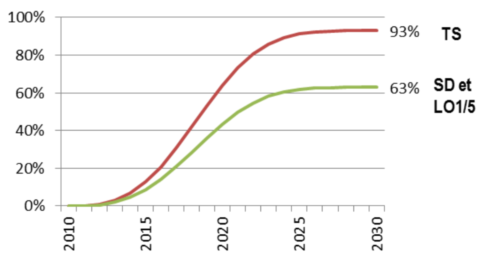
	Technical options	A. Switch to continuous direct seeding (DS)	B. Switch to tillage 1 year in 5 (OT1/5)	C. Switch to superficial tillage (ST)
Technical conditions	**Initial situation**	Reference for 2010: 58% continuous tillage (T), 41% tillage 1year in 2 (T-ST1/2), 1% direct seeding (DS)		
	Change in soil tillage practices	Switch from T or T-ST1/2 to direct seeding (DS) every year	Switch from T or T-ST1/2 to direct seeding with tillage every 5 years (OT1/5)	Switch from T or T-ST1/2 to superficial tillage of the soil (ST) to a depth of around ten centimetres
Unitary abatement potential	**C storage**	Not taken into account with the "CITEPA" method. "Expert" method: ▲ High levels of uncertainty/variability for additional storage		No additional storage
		T → DS: 550 $kgCO_2e$/ha/year (0 to 1,100)	= 65% storage in DS	
	N_2O emissions (direct)	Increase in emissions from soils in DS, with high levels of uncertainty		0
		T → DS: -70 $kgCO_2e$/ha/year (-140 to 0)	= 4/5 of emissions in DS	
	Direct CO_2 emissions (diesel)	Fuel saving (x diesel emission factor)		
		T → DS: 110 $kgCO_2e$/ha/year (104 to112)	= 4/5 of emissions in DS	T → ST: 75 $kgCO_2e$/ha/year(46 to 104)
	Total direct + indirect emissions $kgCO_2e$/ha/year	T → DS: 590 (-36 to 1,212)	T → OT1/5: 389 (-29 to 805)	T → ST: 75 (-25 to 104)
	InducedCO_2 emissions (upstream)	T → DS: Reduction in emissions: ↗ herbicides: -10 $kgCO_2e$/ha/year (-20 to 0) but ↘ fuel: 23 $kgCO_2e$/ha/year (22 to 24)	T → OT1/5: = 4/5 of emissions in DS	T → ST: Reduction in emissions: ↗ herbicides: -4 $kgCO_2e$/ha/year (-8 to 0) but ↘ fuel: 16 $kgCO_2e$/ha/year (10 to 22)
	Total $kgCO_2e$/ha/year	T → DS: 603 (-34 to 1,236) T-ST1/2 → DS: 559 (-23 to 1,173)	T → OT1/5: 400 (-27 to 824) T-ST1/2 → OT1/5: 356 (-16 to 761)	T → ST: 87 (-23 to 126) T-ST1/2 → ST: 43 (-12 to 63)
Unitary cost for the farmer	**Additional benefits**	. Savings in fuel and labour	4 years in 5: . Savings in fuel and labour	. Fuel saving
	Additional costs	. Yield decreases: 2.6% (0 to 5.2%) . Additional herbicide + potentially purchase of equipment	4 years in 5: . Yield decreases . Additional herbicide	. Yield decrease: 0.5% (0-1%) . Additional herbicide
		▲ Calculation highly sensitive to the yield decrease hypotheses associated with DS		
	Total €/ha/year	T → DS: 6 T-ST1/2 → DS: 7 Average cost: 7	T → OT1/5: 3 T-ST1/2 → OT1/5: 4 Average cost: 3	T → ST: -2 T-ST1/2 → ST: 2 Average cost: 0
Potential applicability	**Theoretical potential applicability**	All arable surface areas (14.8 million ha)		
	Technical constraints	Exclusion: 100% of areas cultivated with potatoes and sugar beet and 50% of maize areas (monocropping); poorly drained soils		Exclusion of very poorly drained soils
	Max. Technical Pot. Applicability (MTPA)	10.1 million ha		13.8 million ha
Adoption scenario	**2010 reference situation**	58% CT, 41% T-ST1/2, 1% DS		
	Adoption scenario	Hypotheses: the MTPAs are reached in 2030 		The kinetics are the same irrespective of the initial situation and the technical option targeted; only the scope reached changes.

Table 2

IV- Results and their context

		unit (M: million)	Year 2030			Cumulative value over the period 2010-2030		
			DS scenario	OT1/5 scenario	ST scenario	DS scenario	OT1/5 scenario	ST scenario
Abatement potential ("CITEPA" method)		$MtCO_2e$	1.0 (a)	0.7 (a)	0.8 (a)	11.6 (a)	8.4 (a)	9.4 (a)
Abatement potential ("expert" method)	Without induced emissions		5.7 (-0.3 to 11.8)	3.7 (-0.2 to 7.7)	1 (-0.2 to 1.1)	65.7 (-3.5 to 136.3)	42.7 (-2.7 to 89.6)	11.2 (-2.8 to 13)
	With induced emissions		5.8 (-0.3 to 11.9)	3.8 (-0.2 to 7.9)	0.9 (-0.2 to 1.4)	66.9 (-3.4 to 138.4)	43.7 (-2.6 to 91.3)	10.8 (-2.9 to 15.8)
Total cost for farmers		*€M*	68	30	-3	781	347	-32
Cost per metric ton of CO_2e for the farmer ("expert" method, excluding induced emissions)		*€/tCO_2e*	12 (6 to 233)	8 (4 to 135)	-3 (-2 to 11)	-	-	-

(a) only taking into account fuel

Table 3

• The results

The contribution made by reduced fuel use to the abatement proves to be very significant: it represents 21 to 30% of the abatement in direct seeding and occasional tillage (average estimate) and almost 100% in superficial tillage.

In terms of abatement potential, the scenarios are decreasingly effective: switch to continuous direct seeding (DS) > switch to occasional tillage one year in 5 (OT1/5) > switch to superficial tillage (ST), despite very high levels of uncertainty. The three scenarios can be developed over a very large surface area: from 10.8 to 13.8 million hectares. The additional C storage is uncertain and the potential is likely to be reached in a few decades. Agronomically (evolution in yields and pesticide use, compatible soils), the disadvantages decrease in the same way: DS > OT1/5 > ST. Economically, the first two scenarios have a cost, whereas the third - ST - presents a negative cost. Even for the "costly" scenarios, the cost per metric ton of CO_2e for the farmer remains at most €121 for a moderate abatement.

Comparisons with the results of other studies. The effect of no-till cropping practices on all GHG emissions in the French agricultural context had not previously been assessed. The 2002 INRA collective expertise study[7] had estimated C storage potentials in the soil to be slightly higher than those calculated here. However, the unitary abatement potential values are very similar to those estimated for Ireland and in an international synopsis for cold and damp climates.

• The sensitivity of the results to the hypotheses

The results are highly sensitive to the uncertainties with respect to the magnitude of the phenomena and the hypotheses adopted, both for the emissions and the costs of the measure (see the "ranges"). In terms of the effect of practices, the "direct seeding" option is relatively well covered in the literature and by long-term trials, but there is little information concerning occasional tillage or superficial tillage cultivation.

As regards the **abatement potential**, the differences between the upper and lower values for the estimated unitary abatement potentials primarily come from the C storage component (difference of ±550 tCO_2e /ha/year), followed by the N_2O emissions (difference of ±70 tCO_2e /ha/year) and the fuel saving (±61 tCO_2e /ha/year). However, calculation of N_2O emissions is associated with a high level of scientific uncertainty given their significant variability in terms of both space and time and the high global warming potential of this gas. Unlike the other measures, this one presents an abatement range that includes negative values.

As regards the **economic assessment**, the variability is also very high, depending on whether "pessimistic" or "optimistic" cost estimates are adopted, and particularly concerning the yield decreases associated with no-till farming.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effect

The CITEPA inventory conducted on the basis of IPCC 1996 does not quantify additional carbon storage related to soil tillage methods. The tier 1 method of the 2006 IPCC guidelines can be used to take into account effects on the soil's C stores, but presents limitations (linear kinetics, higher reference values than those in the international literature for superficial tillage); and it does not incorporate N_2O emissions. The calculation method presented in this data sheet, proposing C storage coefficients and N_2O emission factors specific to French agronomic, soil and climate conditions could be used as the basis for an "expert" method for calculation of the impacts of soil tillage on GHG emissions.

Verifiability of implementation

The 2002 INRA collective expertise study had highlighted the difficulties related to verifying additional C stores in general (variability of the phenomenon, etc.), as well as those associated with modifications in cultivation practices in particular (difficult to prove and verify). Although difficult, verification of no-till adoption is possible.

• The contexts and measures liable to promote the roll-out of the measure

Although the effect of reducing tillage is relatively beneficial to farmers in certain hypotheses, the reasons for its non-adoption

[7] Arrouays et al. *Contribution à la lutte contre l'effet de serre. Stocker du carbone dans les sols agricoles de France ?* Collective scientific expertise study (ESco), INRA

need to be considered. Weed control difficulties may be one of the explanations. Difficult-to-quantify additional costs are also likely to be factor -the cost of the seed drill was introduced to take into account a proportion of these costs in one of the scenarios.

One simple incentive measure would be to eliminate the tax exemption on agricultural diesel and replace it with a uniform aid per hectare. If the costs are quantified at the price of taxed fuel, these costs become negative in the three options, but farmers suffer a fall in income, of €40 per hectare with tillage and €23 with direct seeding. A uniform compensatory subsidy per hectare, of about €30, would promote fuel-efficient soil tillage methods.

No-till cropping practices are already adopted spontaneously by farmers (on 21% of annual crop surface areas in 2001, 34% in 2006), due to the resulting fuel and labour savings: this involves a switch to superficial tillage, often with periodic tillage, adoption of which is proportional to the farm size. However, the adoption of direct seeding (given precedence in this measure) is only marginal (1% of annual crop surface areas in 2006).

No-till is promoted to prevent erosion ("conservation" agriculture), with favourable effects on soil fauna. It benefits from a "green" image although its adoption is governed by a broad variety of motivations and it is often associated with an increased use of herbicide.

• Other effects of the measure

Positive effects:

- Improved aggregate stability, reduced run-off and erosion prevention;
- Improved biodiversity and biological activity in soils;
- Effects of fuel and labour savings on farm profitability.

Negative effects:

- Tendency towards increased herbicide use to reduce weed populations and potential impacts on water and crop quality;
- Effects on national production due to (limited) yield reductions.

• Conclusions

No-till cropping methods have a known GHG emission abatement potential that is confirmed by this analysis. This abatement potential results from two main aspects: C storage in the soil and fuel savings. However, it may be significantly reduced by the potential N_2O emissions. The abatement potential calculations are subject to a very high level of uncertainty, and also include situations in which the implementation of simplified cultivation methods increases total GHG emissions (*via* N_2O emissions).

It is the OT1/5 option - "intermediate" in terms of both abatement potential and constraints - that is used for the comparative analysis of the 10 measures.

4 Introduce more cover crops, vineyard/orchard cover cropping and grass buffer strips in cropping systems in order to store carbon in the soil and limit N_2O emissions

↘ CO_2
↘ N_2O

A. Develop cover crops sown between two cash crops in arable farming systems
B. Introduce cover cropping in vineyards and orchards
C. Introduce grass buffer strips alongside water courses or around the edges of fields

I- Challenge and principle of the measure

The GHG balance of agriculture can be improved by increasing carbon storage in the soil by returning larger quantities of organic matter to the soil. Planting cover crops on arable land or herbaceous cover in orchards, vineyards or along water courses, is one possible option.

Three practices were analysed, corresponding to:
- the sowing of cover crops between two main crops for arable systems (3 to 6 months of temporary cover crops depending on the length of the fallow period);
- the planting of cover crops in vineyards and orchards (temporary or permanent herbaceous cover between rows of vines or trees);
- the planting of grass buffer strips alongside water courses or around the edges of cultivated fields (permanent cover).

These practices are already in use, particularly through the application of the "Nitrates Directive" (catch crops) or of CAP cross-compliance (grass buffer strips), or due to their beneficial agricultural effects (bearing capacity of soil improved by green cover in orchards and vineyards, for example). The measure pertains to their extension or generalised use.

II- Mechanisms and technical methods of the measure

The main effect targeted is greater carbon storage in the soil as a result of additional quantities of plant organic matter. Ground cover is also likely to reduce N_2O emissions as a result of nitrogen fixation in the soil. Finally, modifications in nitrogen fertilisation and cropping practices related to the planting of these crops have an impact on other GHG emissions (CO_2).

Few scientific references are available concerning the effects of cover crops between two main crops or in vineyards and orchards, or grass buffer strips on GHG emissions. However, cover crops have recently been examined in bibliographic analyses carried out as part of the 2002 INRA expertise study[8] dedicated to carbon storage in soils and the 2012 INRA study[9] on fallow period management.

• Effects on carbon storage in the soil

Additional C storage in the soil is the result of cover crop residues incorporated by tillage or above-ground and root residues of perennial herbaceous cover (cover cropping in vineyards/orchards and grass buffer strips)

For **cover crops**, the biomass produced depends on the species planted, the growth period and the climatic conditions during development; C storage is dependent on the composition (for example the C/N ratio) of the crop residues. The value used is taken from the 2012 INRA study. This storage is not taken into account for previous crop volunteers since their growth is very random.

Since there is little information in the literature concerning the effects of **cover cropping** in vineyards and orchards, the additional C storage is calculated with reference to other situations: the storage value for grassland cover (value taken from the 2002 INRA expertise study) was used for perennial green cover, and the value for a cover crop (value taken from the 2012 INRA study) for temporary winter cover. On these bases, storage is calculated taking into account the type of green cover practised: either total cover, or 2/3 of the surface for green cover between all the rows.

Grass buffer strips are considered in the same way as grassland; additional storage (value taken from the 2002 INRA expertise study) only occurs if they follow an annual crop.

The calculations are made with two values - lower and upper - obtained from the mean, with the standard deviation value subtracted or added (Table 1). Storage in the soil does not occur at a constant rate and is limited over time. However, it is assumed to be constant over the period considered (2010-2030), and the maximum is reached in 2030.

Additional C storage in soil ($tCO_2e/ha/year$)	
Sown cover crops Previous crop volunteers	0.874 ± 0.393 0
Cover crops in vineyards/orchards permanent cover, 100% surface area permanent cover, between every row temporary winter cover	 1.798 ± 0.954 1.187 ± 0.630 0.584
Grass buffer strip replacing - a cultivated crop - grassland	1.798 ± 0.954 0

Table 1. Storage values taken from the literature

• Effects on N_2O emissions from the soil

A distinction is made between "direct" N_2O emissions from soil in a field and "indirect" emissions (nitrate leaching and ammonia volatilisation) from areas close to the farm. These direct and indirect emissions - highly variable in terms of both space and time - depend on nitrogen fertiliser applications as well as numerous

[8] Arrouays et al. *Contribution à la lutte contre l'effet de serre. Stocker du carbone dans les sols agricoles de France ?* Collective scientific expertise study (ESco), INRA
[9] Justes et al., 2012. *The use of cover crops to reduce nitrate leaching. Effect on the water and nitrogen balance and other ecosystem services.* Synopsis of the study report, INRA, 60 p.

environmental factors (soil type, climatic conditions, etc.). The covers studied can potentially modify N_2O emissions due to their own specific effects and to changes in fertilisation practices as a result of planting them.

Cover crops (CC) are liable to reduce N_2O emissions by taking up nitrate and ammonium present in the soil. However, the bibliographic synopsis of the 2012 INRA study concludes that emissions are increased by 0.1 kgN/ha/year (±1.12 kgN/ha/year) in the year following the CC, depending on the sites. This highly variable result, and the lack of references concerning legume cover crops, lead to these emissions being excluded from the calculations made.

For **cover crops in vineyards and orchards**, the data available are sparse and have been obtained in soil and climate conditions differing from those prevalent in France. In addition, the results are variable. The effect of this cover crop on reducing N_2O emissions will not be taken into account.

Grass buffer strips have not been the subject of specific studies in this area.

However, the impacts of changes in **nitrogen fertilisation practices** are counted. Thanks to the "nitrate-trapping" effect of the CC, the amount of mineral fertiliser applied can be reduced on the subsequent spring crop; this reduction is greater following a legume CC, the residues of which have a higher nitrogen content. Cover crops in vineyards lead to an increase in fertiliser applications to compensate for the nitrogen taken up by the cover. The application of fertiliser is banned on grass buffer strips along water courses.

• Other effects of the measure on GHGs

Planting ground cover leads to a change in cropping practices liable to affect other GHG emissions:

- additional farming operations (sowing, maintenance of herbaceous cover, CC destruction), or, conversely, fewer operations than for a cultivated crop, have an impact on diesel consumption and hence direct CO_2 emissions;
- modifications in mineral nitrogen fertilisation, fuel consumption and plant health practices have an impact on "induced" emissions related to the production and transport of these inputs.

• The sub-measures studied

A. Cover crops. Three technical levers are analysed: (A1) for all existing CCs, systematically reduce nitrogen fertiliser application to the crop that follows and favour the planting of legume CCs; (A2) in "non vulnerable" zones (NVZs) of the "Nitrates Directive", plant CCs in long fallow period situations (5 to 8 months) and reduce nitrogen fertiliser application on the following crop; (A3) promote previous crop volunteers (oilseed rape, straw cereal, etc.) in NVZs.

B. Cover crops in vineyards/orchards Three levers are put forward: (B1) permanent cover of the entire surface area for all orchards; (B2) permanent cover between every row for some vineyards; (B3) temporary winter cover for other vineyards.

C. Grass buffer strips. Only the planting of a grass buffer strip a few metres wide along water courses, in place of an annual crop or grassland, was studied.

III- Calculations of the abatement potential and cost of the measures

• Systems and calculation methods used

The situations used for the calculations and the data sources available are as follows:

A. Cover crops:

A1. Favour the planting of CCs made up of legumes on 15% of CC surface areas (to avoid excessively frequent return times in the same field, generating plant health risks). The reduction in fertiliser application to the next crop, for a CC producing an average of 2 tMS/ha, is estimated to be 5 kgN/ha following a Poaceae or Phacelia CC, 10 kgN/ha following a Brassicaceae and 20 kgN/ha following a CC made up of legumes.

A2. Develop the planting of new CCs in NVZs. The reductions in nitrogen fertiliser applications to the crop that follows are the same as in option A1. Changes in farming practices will be taken into account, such as destruction of the CC by ploughing in on 80% of surface areas or using a herbicide on 20%.

A3. Promote the growth of crop volunteers. Due to their random growth, no change in nitrogen fertiliser applications to the following crop is envisaged. Only changes in practices related to their destruction will be taken into account.

B. Cover Crops in vineyards/orchards:

B1. Extend permanent cover to all orchard surface areas. Only C storage in the soil will be counted.

B2. Extend permanent cover between every row to all vineyards located in zones with a non-limiting water supply. The calculations concern C storage and changes in cultivation practices, which are variable depending on the initial situation (bare soil, temporary cover or herbaceous cover every second row).

B3. Develop temporary cover in vineyards where the water supply is a limiting factor (Languedoc-Roussillon and PACA region). Carbon storage and changes in cultivation practices are quantified.

C. Grass buffer strips:

Along water courses, grass buffer strips replace either a crop (on 40% of surface areas), or grassland (on 60%). The reduction in fertiliser application is estimated to be, on average, 85 kgN/ha/year (with average nitrogen fertiliser quantities on a crop or grassland in France being estimated to be 138 kgN/ha/year and 50 kgN/ha/year, respectively).

The surface area data are obtained from the 2010 Annual farming statistics (SAA).

• Effects of the measure on GHGs and calculation of its unitary abatement potential

The calculations are made using the method defined by the IPCC in 1996 (used by the CITEPA for 2010 emissions), then with the method adopted by the IPCC in 2006 (revision of the values for some emission factors and incorporation of C storage in soils, lower value and upper value). The results presented in Table 2 correspond to those of the second assessment ("expert" calculation).

Target effect:

. **Additional C storage in the soil.** C storage is not currently counted in the national inventory ("CITEPA" calculation). An "expert" method is proposed here, based on the scientific literature and using the values in Table 1.

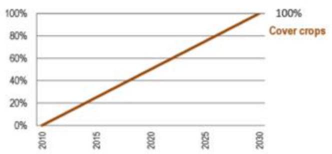
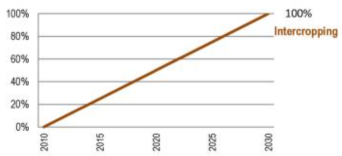
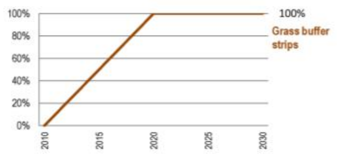
	Sub-measures	A. Cover crops	B. Cover crops in vineyards/orchards	C. Grass buffer strips
Technical content	**Initial situation**	CCs imposed on "Nitrate" vulnerable zones (VZs), for long fallow period situations	92% of orchards already have cover Variable cover depending on wine-growing regions	Edges of water courses already grassed: surface areas not quantified
	Planting of cover	A1: reduce nitrogen fertiliser application to the crop following the CC, propose CCs composed of legumes on 15% of surface areas (all zones combined) A2: propose CCs in non-vulnerable zones (NVZs), for long fallow period situations A3: promote previous crop volunteers in NVZs	Propose cover crops: B1: permanent, on 100% of surface areas in orchards B2: permanent, between every second row, in some vineyards B3: temporary over the winter in some vineyards	Plant grass buffer strips along water courses, replacing a crop (40% of surface areas) or grassland (60%)
Unitary abatement potential	**Additional C storage** kgCO₂e/ha/year	A1: 0 because CC already compulsory in VZs A2: 480 to 1,265 A3: 0	B1: 1,798 ± 954 B2: 1,187 ± 630 (depending on initial situation) B3: 584	After crop: 1,798 ± 954 After grassland: 0
	N_2O emissions (direct + indirect)	↘ in fertiliser application to crop following the CC, variable depending on CC type ↘ of 11 kgN/ha/year: 60	B1: not calculated B2: ↗ due to +30 kgN/ha/year: -170 B3: 0 because no additional fertiliser	↘ due to non-fertilisation (-85 kgN/ha/year): 488
	Direct CO_2 emissions (diesel) kgCO₂e/ha/year	A1: 0 because already CC ↗ agricultural work (↗ diesel consumption): A2: -62 A3: -50	B1: not calculated B2: variable depending on initial situation B3: ↘ agricultural work (↘ diesel consumption): 20	↘ in agricultural work not quantifiable (diesel saving)
	Total direct + indirect emissions kgCO₂e/ha/year	A1: 61 A2: 479 to 1,264 A3: -45	B1 = 844 to 2,753 B2 = 1,078 B3 = 587	822 to 1,578
	Induced CO_2 and N_2O emissions (upstream) kgCO₂e/ha/year	A1: 56 A2: 40 A3: -10	B1: not calculated B2: variable depending on initial situation B3: ↘ agricultural work (↘ diesel and herbicide consumption): 20	Fertiliser application: 450 A non-quantified proportion (↘ in agricultural work)
	Total kgCO₂e/ha/year	A1: 118 A2: 520 to 1,305 A3: -58	B1: 844 to 2,753 B2: 46 to 999 B3: 610	1,270 to 2,029
Unitary cost	**Saving/purchase of inputs** **Labour for cover**	Fertiliser savings A1: none, since CC already compulsory A2: CC planting and destruction A3 : crop volunteer destruction	B1 & B2: cover planting and maintenance (3 cuts/year) B2: purchase of fertiliser B3: planting and destruction	Fertiliser and pesticide savings 1 cut/year
	Production losses	0	B2: ↘ in production in terms of quantity and quality not quantified	↘ in production on the green cover surface area
	Total €/ha/year	41 (all operations combined)	10 (all operations combined)	633
Potential applicability	**Theoretical potential applicability**	A1: all zones (VZs and NVZs) A2 and A3: surface areas before a spring crop in NVZs	All orchards Some vineyards	All edges of water courses identified on an IGN map with a scale of 1/25 000
	Technical criteria	Exclusion of soils with a clay content >60% A1 and A2: a CC composed of legumes / 6 years	B2 and B3: exclusion of soils with a high coarse element content B2: exclusion of vines in dry climates	
	Max. Technical Pot. Applicability (MTPA)	A1: 2.829 Mha A2: 1.070 Mha A3: 0.352 Mha	B1: 13,800 ha B2: 127,900 ha B3: 71,300 ha	250,000 ha
Adoption scenario	**2010 reference situation**	CC in the 2006 "Cropping practices" survey (under-estimated because CC obligation has come into effect since) A2: CC already on 8% in NVZs	B1: 92% of orchards already have cover crops B2 + B3: 415,900 ha already have cover crops	Grass buffer strips not counted but numerous
	Adoption scenario	MTPA reached in 2030 	MTPA reached in 2030 	↗ CAP cross-compliance "maintenance of landscape features" in 2013 ➔ MTPA reached in 2020 

Table 2

Other effects quantified (N_2O and CO_2):

. Modification in direct and indirect N_2O emissions. Following changes in nitrogen fertilisation practices, emissions are calculated using the emission factors provided by the IPCC in 2006.

. Evolution in direct CO_2 emissions. Emissions linked to the additional fuel consumption for planting, maintaining and destroying CCs or herbaceous cover are calculated using the emission factors determined from the Carbone® database.

. Induced effects (upstream of the farm). Induced emissions, related to the production and transport of mineral fertilisers, herbicides and diesel, are calculated using data from the Dia'terre® - Ges'tim database.

Effects ignored or not quantified:

- Modifications in direct N_2O emissions linked to the presence of a CC (mineralisation of residues) or herbaceous cover in orchards, vineyards and along water courses.
- The reduction in indirect N_2O emissions related to reduced nitrate leaching and ammonia leaching from soils carrying this cover.
- Induced emissions associated with the production and transport of minor inputs (cover crop seeds, etc.).

• Estimation of the unitary cost for the farmer

These costs include:
- savings or additional costs associated with nitrogen fertilisers,
- expenditure linked to planting and managing cover;
- production losses as a result of planting grass buffer strips (which reduce the production area).

The agricultural practices adopted should enable maintenance of production levels for crops following CCs and for vineyards and orchards newly planted with cover. Any impact on the quality of the grapes and wines could not be globally estimated.

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

A: It consists of current CC surface areas, plus surface areas cultivated with spring crop varieties in "Nitrates Directive" non-vulnerable zones. Land unsuitable for the planting of CCs (soils with a high clay content, >60%) are excluded.
B: It concerns all orchards and vineyards, excluding areas where the soil has a high coarse element content. The technical option is chosen depending on the water supply conditions.
C: All areas along water courses identified on an IGN map with a scale of 1/25000 are concerned, i.e. 250,000 ha (GAEC file, Buffer strip).

Areas to be excluded due to their soil characteristics (clay content too high or too stony) are estimated by comparing the surface areas concerned and data from the *Corine Land Cover* map.

Measure adoption scenario

The 2010 reference situation was described using the statistical data available, which are slightly dated (2006 "Cropping practices" survey) for CCs, incomplete for some vineyards and absent for grass buffer strips.
Adoption of the three sub-measures was considered to be progressive and steady over time. The maximum theoretical potential applicability is reached by 2020 (C) or in 2030 (A and B).

IV- Results and their context

		units (M: million)	Year 2030				Cumulative value over the period 2010-2030		
			Cover crops	Cover crops in vineyards/ orchards	Grass buffer strips	**Total 3 sub-measures**	Cover crops	Cover crops in vineyards/ orchards	Grass buffer strips
Abatement potential ("CITEPA" method) without induced emissions		*$MtCO_2e$*	0.3	-0.02	0.2	**0.5**	3.3	-0.2	3.2
Abatement potential ("expert" method)	without induced emissions		1.1* [0.7 / 1.5]	0.14* [0.07 / 0.2]	0.3* [0.2 / 0.4]	**1.5* [0.9 / 2.1]**	11.8* [7.2 / 16.3]	1.6* [0.8 / 2.4]	4.7* [3.2 / 6.2]
	with induced emissions		1.3* [0.9 / 1.7]	0.13* [0.06 / 0.2]	0.4* [0.3 / 0.5]	**1.8* [1.2 / 2.4]**	13.9* [9.4 / 18.5]	1.5* [0.7 / 2.3]	6.5* [5.0 / 7.9]
Total cost for farmers		*€M*	173.9	2.0	158.3	**334.3**	1891	22	2468
Cost per metric ton of CO_2e for the farmers ("expert" method, without induced emissions)		*€/tCO_2e*	160	14	528	**219**	-	-	-
			(115 to 260)	(10 to 34)	(402 to 771)				

* The mean values are arithmetic means between the lower values (high C storage hypothesis) and upper values (low C storage hypothesis) used for the emission factors, except in the case of the cost per metric ton of CO_2e.

Table 3

• The results

Compared to the "CITEPA" calculation (based on the 1996 IPCC recommendations), taking into account C storage in the soil and the evolution in emission coefficient values related to mineral nitrogen fertilisers as proposed by the IPCC in 2006 significantly improves the abatement potential of these three sub-measures. Of these, the adoption of CCs leads to the highest potential. This result can be explained by the large surface area targeted by this sub-measure, since the unitary abatement potential is not particularly high. However, the cost per metric ton of CO_2e avoided is high, as a result of the numerous cultivation operations. The abatement potential linked to introducing cover crops in vineyards and orchards is relatively low and this sub-measure concerns few hectares. The cost is not very high since there is little change in cultivation practices. For grass buffer strips, despite a high unitary abatement potential, the overall result is low due to the limited surface areas concerned by this sub-measure. Their adoption is accompanied by a high cost for farmers due to a loss of income from these surface areas.

• The sensitivity of the results to the hypotheses

Quantification of the unitary and overall abatements is highly sensitive to various parameters. The lack of accurate data (technical references in vineyards) or the use of old data (cropping practices for CCs) lead to numerous hypotheses being formulated and some calculations being simplified.
The following were not counted:
- the variation in biomass production of CCs. The value used is 2 tMS/ha/year on a France-wide scale, despite the fact that it fluctuates greatly (0 to 5 tMS/ha/year),
- the effect of CCs on a reduction in nitrate leaching (since not quantified),
- some wine-growing regions (statistical data absent),
- the surface areas already grassed along water courses in 2010 (data not available),
- the reduction in N_2O emissions following the adoption of the different technical levers (highly variable depending on the soil and climate conditions, and for which there are very few data).

The surface area (25 ha) of elementary parcels, used in the *Corine Land Cover* project to calculate surface areas with a high clay content and surface areas with a high coarse element content, is not suitable for the plot sizes analysed.
To define the maximum technical potential applicability of grass buffer strips, the hypothesis used is to assign them the entire Landscape Element Equivalent Area, whereas this can also be assigned to hedges, wooded areas, walls, etc.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effect
The "CITEPA" method does not take into account either additional C storage in the soil or revision of the emission values of mineral nitrogen fertilisers. The calculation rules used by the IPCC in 2006 led to changes in the emission coefficients linked to fertilisers and enabled assessment of C stores.

Verifiability of implementation
Implementation of these sub-measures could be assessed either by means of surveys conducted among farmers, or by taking aerial photographs to identify whether ground is covered by vegetation.

• The contexts and measures liable to promote the roll-out of the measure

The technical options proposed for cover crops and grass buffer strips are not difficult to implement and do not require any specific equipment. However, in some vineyards, cover crops will be difficult to plant (for goblet-pruned vines or high vine density situations) and sometimes require the purchase of specific equipment.

The development of the different technical levers identified for **cover crops** is difficult to quantify. There are obstacles hampering the reduction of nitrogen fertilisation of crops (see "Nitrogen fertiliser application" measure) and planting new CCs generates additional financial costs that are not insignificant.

It is difficult to quantify the evolution in **vineyard cover crops**. The future of vine-planting rights dictated by the new CAP has not yet been set. European regulations could have an impact on farming practices, including the introduction of cover crops. In parallel, agronomic initiatives contained within the Ecophyto 2018 plan are relatively favourable to the development of cover crops in French vineyards. However, uncertainties concerning the technical management of vineyards with cover crops and the vinification of their products need to be taken into consideration.

The generalisation of **grass buffer strips** along water courses is subject to CAP cross-compliance rules, which are favourable to them.

• Vulnerability and adaptability of the measure to climate change

Climate change that would result in lower rainfall and higher temperatures would reinforce competition for water, either between main crops and cover crops or between fruit trees or vines and herbaceous cover. In these limiting contexts, the introduction of CCs or cover crops in orchards or vineyards would be less developed. In addition, the risk of a shortage of water for irrigation could lead to a reduction in surface areas of summer crops - highly water-dependent - and a reduction in CC surface areas.

• Other effects of the measure

Impacts on production
The introduction of cover crops in vineyards is likely to have a negative effect on production, but few references exist. In Alsace, the presence of herbaceous cover does not modify production in deep, fertile soil situations, but reduces it by 20% on shallow soils, despite the application of 40kgN/ha/year. Furthermore, a change in the quality of grapes and musts may require the adjustment of wine-making processes. Planting **grass buffer strips** leads to a loss of production when the surface areas were initially used for cultivated crops or grassland.

Agronomic and environmental impacts
Cover crops between main crops and **cover cropping in vineyards/orchards** have demonstrated effects on increasing the mineralisation potential of organic matter stored in soils, reducing water and air erosion phenomena and improving the physical properties of soils (reduction in run-off and sealing, decompaction). In vineyards, cover crops constitute an ecological niche for beneficial insects, enabling better control of some pests. **Grass buffer strips** help to reduce water pollution by nitrates and plant health products.

• Conclusions

Cover crops
Planting a cover crop is not technically difficult to implement, excluding certain emergence difficulties in the event of post-sowing drought. The repeated incorporation of cover crop residues may lead to an increase in the mineralisation of organic matter stored in soils, making it possible to maintain the production levels of the crops that follow. However, despite their positive impacts on the environment and the absence of any detrimental effect on the production of the next crop, their adoption represents a financial cost to the farmer.

Cover crops in vineyards/orchards
In some conditions, introducing cover crops in certain vineyards can be tricky and sometimes requires the purchase of specific equipment. Despite the positive environmental effects already demonstrated, the adoption of this practice by vine growers is not widespread due to quantitative and qualitative modifications in wine production that cannot be specifically quantified in each vineyard.

Grass buffer strips
The option proposed is not technically difficult to implement and provides numerous environmental benefits. Its major drawback is that it reduces production surface areas and hence generates income losses for farmers.

↘ CO_2

❺ Develop agroforestry and hedges to promote carbon storage in soil and plant biomass

A. Develop agroforestry with a low tree density
B. Develop hedges around the edges of fields

I- Challenge and principle of the measure

The GHG balance of agriculture can be improved by increasing carbon storage in biomass or in the soil in the form of organic matter, i.e. from CO_2 absorbed by plants. This storage can be increased by the development of ligneous biomass or by returning more organic matter to the soil.

The measure targets the planting of trees within agricultural parcels that are cultivated with arable crops or in grass (agroforestry) or around their edges (hedges). The scenarios selected are low-density tree planting (30-50 trees per ha) and the establishment of 60 or 100 linear metres of hedgerows per ha, situations that are compatible with the maintenance of mechanised agricultural production.

II- Mechanisms and technical methods of the measure

• Methods and benefits of introducing trees

"Agroforestry" is a generic term used for an agricultural production method combining trees with arable crops or grassland Common in Europe in the past, these practices were gradually abandoned over the course of the 20th century, primarily for reasons related to the intensification and mechanisation of agriculture. A "modern" form of agroforestry has recently emerged, combining lines of trees with mechanised cover cropping in vineyards/orchards.

In this study, the "agroforestry" sub-measure corresponds to the introduction of trees within crop fields or grass and the "hedges" sub-measure corresponds to the introduction of trees around the edges of fields. The definition for hedges is the one used in the French national forestry inventory[10].
Independently of its environmental benefits (carbon storage and others), the value of agroforestry resides in the hypothesis that its total biomass production (trees + agricultural production) per hectare will be greater than that obtained on separate areas.

Agroforestry presents a broad diversity of systems, which differ in terms of the tree species planted, their density and their arrangement within the field. The available results concerning the operation and productivity of these systems are sparse and usually limited to the first few years following planting of the trees. These references often focus on an assessment of the biophysical and technical effects of agro-forestry. For an integrated technico-economic approach, the few references available come mainly from the European Silvoarable Agroforestry For Europe (SAFE) research project, which studied agroforestry systems using 5 species (holm oak, umbrella pine, poplar, cherry and walnut).

As regards **hedges**, their definition covers a broad diversity of practices, with planted or spontaneous hedgerows, with low, shrub or tree vegetation, trimmed or otherwise, planted on flat ground or on an embankment.

• Effects on carbon storage

The additional carbon storage in agroforestry cultivated land or grassland or fields surrounded by trees results primarily from:

- storage in perennial plant biomass (above-ground and underground),
- the return of organic matter to the soil via litter (dead leaves), the renewal of fine roots and root exudates.

Storage in ligneous biomass depends on the fate of the wood produced: it will be several decades or even hundreds of years for construction timber, but considered to be nil for products used as heating wood, burned within the year. By replacing fossil fuels, the latter use helps to reduce CO_2 emissions. Trimmed branches can also be mulched and incorporated into the soil, adding to the carbon store.

•The sub-measures studied

Agroforestry. An analysis of the literature concerning additional carbon storage in trees and in the soil reveals a high level of variability in the storage levels measured depending on the soil and climate context, the type of agroforestry system (in particular, the tree density) or the method used (soil depth taken into account, etc.). Very few measurements have been performed in temperate climates.
The analysis of the literature led to a value of **3.7 tCO_2**e/ha/year being retained for carbon storage in biomass and in the soil, over a 20-year period, with a lower value of 0.4 tCO_2e/ha/year and an upper value of 4.97 tCO_2e/ha/year. It can thus be seen that agroforestry storage is associated with a very high level of uncertainty.
It should be noted that the carbon storage rate is not constant and therefore the value used should be considered to be an average value, "linearised" over a 20-year period.

Hedges. Few studies have quantified additional C storage in the soil associated with the planting of hedges in temperate environments. The values adopted are **0.55 tCO_2**e/ha/year (lower value: 0.17 and upper value: 0.94) **and 0.92** (lower value: 0.28 and upper value: 1.56), depending on whether the hedge is introduced in a cultivated field or grassland, over 60 or 100 linear metres, respectively. These values are lower than those measured in certain studies, but consistent with recycling of hedge products as heating wood, leading to only the carbon in the roots and soil being considered to be stored in the long term.

• Other effects of the measure on GHGs

The reduction in erosion related to the presence of trees was considered to have no effect on GHG balance insofar as the

[10] A hedge is a linear tree formation consisting of trees and bushes, at least 25 metres long and with no break in excess of 10 metres and with a base width of less than 20 metres (80% of the biomass being concentrated on a width of less than 2 metres) and a potential height of over 2 metres.

organic matter displaced by erosion can be re-deposited and accumulate downstream of the field.

The introduction of trees reduces the cultivated surface area, and hence input consumption (fertilisers, pesticides, diesel) and agricultural production output per hectare. It is liable to modify management of the crop: reduction in fertiliser application (made possible by the organic matter supplied) or irrigation (under the shade of trees).

III- Calculations of the abatement potential and cost of the measures

• Systems and calculation methods used

The systems used as a reference are:
- for **agroforestry**: low-density planting (around 30 to 50 trees/ha), left in place for at least 20 years; for the economic assessments, three species are considered (poplar, cherry and walnut);
- for **hedges**: planting of 100 linear metres (lm) of hedge per ha of grassland and 60 lm per ha of crops.

In agroforestry, the index most commonly used to evaluate the global productivity of the associated crops is the *Land Equivalent Ratio* (LER). This is interpreted as the area that would need to be cultivated with sole crops (agricultural control and forestry control) to produce as much (and in the same proportions) as is produced by a hectare of planted agroforestry land[11]. Few assessments of this LER in temperate conditions have been carried out. In this study, the calculations were performed assuming an LER of 1.3.

As regards the fate of wood, the hypothesis adopted is long-term storage for timber (construction timber) for agroforestry, and zero storage for the above-ground biomass of hedges, used for heating (sale for the production of wood chips) - but this production of wood for energy represents fuel savings.

Introducing trees leads to a reduction in the surface area assigned to cultivated crops or grass, estimated to be 5% for the agroforestry sub-measure and 1.2 to 2% for the hedges sub-measure. For agroforestry, the production losses (due primarily to shade) are estimated on the basis of the LER. It is assumed that the costs remain proportional to the product, with, however, a slight additional cost. The initial gross margins are taken from the RICA 2010 database, and the data concerning crop and grassland management (fertiliser consumption, for example) are derived from the 2006 "Cropping practices" survey. All the calculations are made by differentiating between arable crops and grassland (temporary or permanent), for which the surface areas are provided by the 2010 Annual farming statistics (SAA) database.

The diversity of regional situations, which affect the production levels of crops and grassland, as well as the growth and productivity of trees, could not be taken into account; the data used are nationnal averages. The potential effects on crop and grassland management due to the presence of the trees were not considered either.

For grassland, the results of the SAFE project should be considered with caution, since few economic studies have examined sylvopastoralism.

• Effects of the measure on GHGs and calculation of its unitary abatement potential

In the 2010 national inventory, windbreak hedgerows, and tree screens and corridors are included in forests if they have a surface area of over 0.5 ha and a width of over 20 m; agroforestry plots are counted in the "crop" category. Neither hedges nor agroforestry can therefore be taken into account. The inventory does not count C storage in the soil and considers storage in ligneous biomass to be nil, assuming that the increase compensates for harvesting, following which all the wood is burned during the year subsequent to its harvest.

In this study, the abatement potential related to the introduction of agroforestry and hedges will therefore be calculated mainly on the basis of an effect-by-effect compilation of the values available in the literature.

Target effect:

. **Additional carbon storage** in soil and tree biomass. The additional storage values used are those adopted previously: +3.7 (0.4-4.97) tCO_2e/ha/year for agroforestry, and 0.55 (0.17-0.94) and 0.92 (0.28-1.56) tCO_2e/ha/year for hedges.

Other effects quantified:

. **The reduction in N_2O emissions** related to mineral nitrogen fertilisation, due to the prorata elimination of fertilisers on reduced cultivated areas. These emissions - direct and indirect - are calculated on the basis of average fertiliser applications in France and the emission factors provided by the 2006 IPCC guidelines.

. **The modification in CO_2 emissions** related to additional labour operations for the trees (planting, maintenance and harvesting of trees) and the reduction in the agricultural land worked.

. **Modifications in induced emissions**, related to the substitution of wood obtained from hedge trimming for fossil fuels for heating, as well as to the production and transport:
- of mineral nitrogen fertilisers (induced emissions calculated on the basis of average fertiliser applications in France and the values provided by the Dia'terre® - Ges'tim database);
- of diesel (induced emissions calculated on the basis of the ADEME's Carbone® database);
- of fuel oil (the consumption of which is avoided by turning the wood collected from hedges into energy).

Effects ignored:

- Energy consumption downstream of the farm, linked to use of the harvested product (transport, sawmill, production of wood chips or furniture).

• Estimation of the unitary cost for the farmer

The following costs are taken into account:
- the costs and benefits associated with trees, considered excluding subsidies: planting, maintenance and harvesting costs, and sale of wood;
- the effects of loss of agricultural surface area: input and labour savings, and shortfall due to reduced production.

For agroforestry, the calculation of costs was supported by an update of the results published by the SAFE project. For hedges, a standard management technique for the establishment, maintenance and harvesting of hedges was reconstituted.

The revenues and costs are added together at a discount rate of 4%.

[11] A combination is therefore "globally" interesting from a productive point of view if its LER is greater than 1, i.e. if the combination makes it possible to produce more, per area unit, than sole crops.

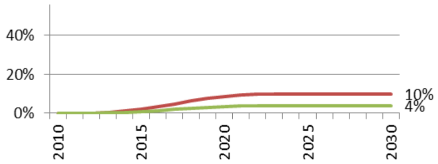
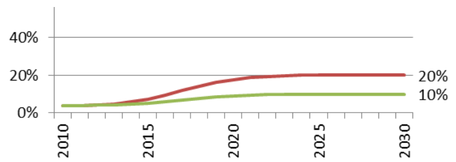
	Sub-measures	A. Agroforestry	B. Hedge planting
Technical content	**Tree planting**	Trees within fields, in annual crops or on grassland (permanent or temporary) Low density (30-50 trees/ha), compatible with maintenance of agricultural production, and access to CAP aids -5% of surface area for annual crops or grassland	Trees around the edges of fields 100 linear metres (lm) per ha of grassland 60 linear metres (lm) per ha of cultivated crops -1.2 to -2% of surface area for annual crops or grassland
Unitary abatement potential	**C storage** $kgCO_2e$/ha/year	In the soil, underground and above-ground biomass: Crops and grassland: 3,700 (400 to 4,970)	In soil and underground biomass Crops: 550 (170 to 940) Grassland: 920 (280 to 1,560)
	Direct CO_2 emissions (diesel) $kgCO_2e$/ha/year	Tree planting, maintenance and wood harvesting work: Additional consumption: -14	Additional consumption: Crops: -3 Grassland: -6
	N_2O emissions (direct + indirect) $kgCO_2e$/ha/year	Fertiliser savings (-5% surface area): Crops: 63 Grassland: 8	Fertiliser savings (-1.2 to 2% surface area): Crops: 15 Grassland: 25
	Total direct + indirect emissions $kgCO_2e$/ha/year	Crops: 3,749 (449 to 5,019) Grassland: 3,694 (394 to 4,964)	Crops: 562 (182 to 952) Grassland: 939 (299 to 1,579)
	InducedCO_2 and N_2O emissions (upstream) $kgCO_2e$/ha/year	Fertiliser savings and increased diesel consumption: Crops: 33 Grassland: 2	Fertiliser saving, increased diesel consumption and conversion to energy: Crops: 690 Grassland: 1,140
	Total kCO_2e/ha/year	Crops: 3,782 (482 to 5,052) Grassland: 3,696 (396 to 4,966)	Crops: 1,252 (872 to 1,642) Grassland: 2,079 (1,439 to 2,719)
Unitary cost	**Planting investment**	▲ Few technico-economic references available From €17 (cherry) to €45 (poplar) per hectare	€15 (plants + labour) per lm i.e. €54/ha/year
	Tree maintenance and production	Around €50 per hectare	Pruning and pollarding, coppicing, weed control, harvesting: €17/ha/year
	Production losses	Crops: from €80 to €124ha/year, depending on tree species Grassland: from €42 to €70/ha/year, depending on tree species	Crops or grassland: €9/ha/year
	Wood use	Sale of construction timber: €84 to €147/ha	Sale of wood: €16/ha/year
	Total €/ha/year	Crops: €54/ha/year (walnut), 45 (poplar), 69 (cherry) Grassland: €28/ha/year (walnut), 52 (poplar), 45 (cherry)	75
Potential applicability	**Theoretical potential applicability**	All arable (13.8 Mha) and grassland (9.8 Mha) surface areas, i.e. a total of 23.6 Mha	
	Technical criteria	Soil with an adequate depth (1 m) and UR (120 mm) Fields of at least 4 ha	Soil with an adequate depth (0.5 m) Fields of at least 4 ha
	Max. Technical Pot. Applicability (MTPA)	Crops: 3.9 Mha; Grassland 1.98 Mha Total: 5.9 Mha	Crops: 7.6 Mha; Grassland 4.5 Mha Total: 12.1 Mha
Adoption scenario	**2010 reference situation**	2,000 ha in 2010	4% of land already has hedges (503,300 ha of hedges)
	Adoption scenario	Scenario with 4% of MTPA in 2030 Scenario with 10% of MTPA in 2030 	Scenario with 10% of MTPA in 2030 Scenario with 20% of MTPA in 2030 

Table 1

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

For the 2 sub-measures, areas still in grass with low productivity (rough grazing, moorland, alpine grazing) are excluded since they are difficult to access (relief).

For **agroforestry**, fields with a size > 4 ha (compatible with mechanisation of labour between tree rows), and with a soil depth > 1 m and a useful water reserve > 120 mm (i.e. 38% of cultivated soil, 31% of grassland). For **hedges**, the same criterion is used for the field size, but the requirement is lower for soil depth, > 0.5 m (i.e. 74% of cultivated land, 71% of grassland).

Measure adoption scenario

For **agroforestry**, which represents a significant change in production strategy, the hypothesis is for slow adoption, with 2 scenarios: adoption on 4 and 10% of the MTPA by 2030.

For **hedges**, the current extension of which can be estimated to cover 4% of land (mainly located in enclosed livestock grazing zones), the hypothesis is once again for slow adoption, with 2 scenarios: adoption on 10 and 20% of the MTPA by 2030.

IV- Results and their context

		units (M: million)	Year 2030			Cumulative value over the period 2010-2030	
			Agroforestry* Average*** [4% / 10%]	Hedges** Medium [10% / 20%]	**Total 2 sub-measures**	Agroforestry* Medium [4% / 10%]	Hedges** Medium [10% / 20%]
Abatement potential ("CITEPA" method) Without induced emissions		*$MtCO_2e$*	0	0	**0**	0	0
Abatement potential ("expert" method)	Without induced emissions	*$MtCO_2e$*	1.5 [0.1 / 2.3]	1.3 [0.3 / 2.9]	**2.8 [0.4 / 5.2]**	17.7 [1.2 / 27.1]	18.1 [4.2 / 38.9]
	With induced emissions	*$MtCO_2e$*	1.5 [0.1 / 2.4]	2.8 [1.3 / 4.9]	**4.4 [1.4 / 7.3]**	17.7 [1.2 / 27.3]	40.2 [20.3 / 67]
Total cost for farmers		*€M*	20.5 [11.7 / 29.2]	136.1 [90.8 / 181.5]	**156.6 [102.5 / 210.7]**	236.5 [135.1 / 337.8]	1931 [1406 / 2456]
Cost per metric ton of CO_2e for the farmer ("expert" method, without induced emissions)		*€/tCO_2e*	14 [13 / 118]	107 [63 / 332]	**56 [41 / 275]**	-	-

* 2 values corresponding to the 2 scenarios: 4% and 10% of the MTPA; ** 2 values corresponding to the two 2 scenarios: 10% and 20% of the MTPA;
***the average values correspond to the introduction of agroforestry on 7% of the MTPA and hedges on 15% of the MTPA, using central potentials and costs. The lower abatement ranges are applied to the low MTPA scenarios and the upper ranges to the high MTPA scenarios.

Table 2

• The results

For **agroforestry**, the unitary abatement potential for direct and indirect emissions is 3.75 tCO_2e/ha/year for crops and 3.7 tCO_2e/ha/year for grassland. The induced emissions are very low (33 $kgCO_2e$/ha/year) for crops and negligible for grassland.

For **hedges**, the unitary abatement potential for direct and indirect emissions is 0.55 tCO_2e/ha/year for crops and 0.92 tCO_2e/ha/year for grassland. The induced emissions are not insignificant given the conversion into energy of the harvest adopted as the hypothesis (0.14 and 0.22 tCO_2e/ha/year for crops and gazing, respectively).

The unitary abatement potential of the "low-density agroforestry sub-measure" is significantly higher than that of the "hedges" sub-measure (3.7-3.75 versus 0.55 and 0.92 tCO_2e/ha/year), which is logical given the proportion of land concerned (1.2 or 2% for hedges compared to 5% for agroforestry) and long-term use in the form of construction timber adopted as the hypothesis for agroforestry. In addition, the unitary cost per metric ton of CO_2e is lower for agroforestry than for hedges (€14 compared to €107). Given the different MTPAs (5.9 million ha for agroforestry and 12.1 for hedges) and the different unitary storage potentials, the average cumulative abatements over the period 2010-2030 are equivalent for the two sub-measures, at around18 million tCO_2e, for a cumulative cost of 237 million euros (€M) in the case of agroforestry, compared to €1,931 M for the "hedges" sub-measure. However, it should be noted that the prospect of reaching 10% of the MTPA in 2030 appears to be much more realistic in the case of hedges (already present on over 500,000 ha of agricultural land in 2010) than for agroforestry using low-density precious wood.

Application of both sub-measures to the same field is unlikely. However, given the low adoption levels considered (a maximum of 10% and 20% of the MTPA for agroforestry and hedges, respectively), the development of the two sub-measures on different areas can be envisaged. Their effects may therefore be cumulative on a national level

It is the average values that will be used for the comparative analysis of the measures.

Comparisons with the results of other "GHG abatement" studies. Several recent reports and expert assessments concerning temperate zones consider the introduction of trees into agricultural land to be a carbon-storing practice. In the USA, the potential for the development of agroforestry over 10 Mha was calculated to be 4.97 tCO_2e/ha/year. In Europe, a study - taking agroforestry storage rates from a French technical expertise study of 5.55 to 14.8 tCO_2e/ha/year, depending on the planting density, duration, rotation and growth rate of the trees - estimated that the potential contribution of agroforestry to carbon storage is very high (1,566 million metric tons of CO_2e per year) on a European scale (EU 27).

• The sensitivity of the results to the hypotheses

The results concerning the environmental and economic efficacy of this measure are associated with a high level of uncertainty due to the large number of hypotheses made. In particular, the hypotheses made to quantify the potential abatement are strong given a lack of references measured in temperate environments in comparable situations, particularly in terms of tree density. The species of trees planted was not taken into account, whereas the growth rate of trees is a decisive factor in biomass production and hence the abatement potential. The value used to calculate carbon storage is realistic, particularly for poplars -a fast-growing tree species - but could be revised downwards for slower-growing species, such as walnut trees. According to the hypotheses made concerning carbon storage, the unitary abatement potential varies by a factor of 10 for agroforestry.

Another strong hypothesis concerned subsequent use of wood, with long-term storage in the form of construction timber for agroforestry, and limited storage in the case of hedges. The hypothesis of construction timber production is debatable, particularly for poplars. This approach is particularly open to criticism since all the carbon stored in the wood is not exported from the fields and only a portion of the logs marketed are converted into more or less long-term products. Ideally, storage in products and storage in vegetation and the soil should be separated.

Estimation of the maximum technical potential applicability is also sensitive to the biophysical and agricultural criteria used. The latter - although reasonable - can be debated: planting trees is also theoretically possible in less favourable situations; other technical feasibility criteria, related to the farm (UAA, equipment, integration within wood supply chains) were not taken into account. The level of adoption of the sub-measures envisaged as a % of the MTPA is also difficult to justify: the two values (realistic and optimistic) used in the study make it possible to frame the abatement estimate up to 2030.

Finally, the **cost** calculations also appear to be highly variable and sensitive to the hypotheses used. The central scenario adopts a cost (although moderate) for the development of agroforestry, whereas the SAFE project concluded that it was - to a certain extent - profitable – this profitability varying, however, depending on the scenarios envisaged. One of the reasons for this is related to the very different agricultural price contexts in 2006 (baseline year for the SAFE project) and 2010 (baseline year for the study). In fact, numerous different variables affect the profitability of agroforestry. In particular, the discount rate chosen (4%) penalises agroforestry considerably, whereas this rate is subject to debate given the apparently lasting stagnation of growth. For the cost calculations, it was necessary to set the level of yield losses resulting from the presence of trees: an LER was set on the basis of the few data available.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effect

In the 2010 national emissions inventory, in the absence of any land use change, variations in C stocks in the soil (and biomass) linked to practices (including agroforestry and hedges) are not counted. To our knowledge, neither hedges nor agroforestry are explicitly and specifically taken into account in the national inventory.

The 2006 IPCC guidelines mention agroforestry as a practice that stores carbon in soil and biomass, which corresponds to conversion of cultivated land or grassland into wooded land, but it does not stipulate any explicit calculation method for estimating the effects of agroforestry.

Verifiability of implementation

Implementation of the measure would be easy to track via the contracting out of measure 222 to local authorities, and verifiable, via satellite imaging, in particular. The association network (Association française d'agroforesterie - AFAF [French Agro-forestry Association], Association française des arbres et des haies champêtres - AFAC [French Association of field trees and hedges]) - which is particularly active - could be a valuable relay to support and monitor development of the measure.

• The contexts and measures liable to promote the roll-out of the measure

Today, agroforestry has been identified by the French Ministry of Agriculture as an innovative and agro-ecological farming practice and as a vector for diversification potentially profitable to farmers. In this context, the French (AFAF) and European (EURAF) agroforesty associations and the AFAC are working to disseminate and support agroforestry.

As part of the Programme de Développement Rural pour l'Hexagone (PDRH - French Rural Development Programme) 2007-2013, agroforestry can be subsidised via four support measures: measure 121-B "*Plan Végétal Environnement, installation de haies et d'éléments arborés*" (Green Plan for the Environment, establishment of hedges and trees); measure 216 "*Investissement non-productif*" (Non-productive investment); MAET (regional agro-environmental measure) 214-I "*Entretien de haies localisées de manière pertinente*" (Maintenance of relevantly-located hedgerows), and (since 2009) measure 222 "*Première installation de systèmes agroforestiers sur des terres agricoles*" (First introduction of agroforestry systems on agricultural land). This measure 222, co-funded by the EAFRD (European Agricultural Fund for Rural Development) and local authorities wishing to participate, can only cover the costs of introducing the trees and maintaining planted areas for the first few years. The subsidy rate may be as high as 70%, or even 80% in disadvantaged zones. The precise specifications for the measure are defined on a regional scale.

The sheer number of current mechanisms and their implementation conditions make them difficult to mobilise. All the measures are zoned, in accordance with the perimeters defined within the scope of Natura 2000, the Water Framework Directive, and Birds and Habitats Directives excluding Natura 2000: this zoning does not cover all regions. In addition, these various measures are associated with minimum thresholds, in terms of surface areas developed and financial budgets, which are very restrictive in view of the surface areas and linear areas targeted in each development (specific to each objective indicated). Finally, the fragmentation of the highly targeted objectives of these measures, along with the indication of field trees as a response to these objectives, makes it difficult to identify the validity of tree planting.

Today, in the context of CAP negotiations, the idea of a **global measure to support agroforestry systems**, incorporating all forms of field tree planting and applicable to all agricultural systems, with no limit in terms of tree density per hectare, is being proposed.

• Other effects of the measure

Politically, **agroforestry** is above all highlighted for its agro-environmental performance, as a method to control soil erosion, groundwater and river pollution, landscape uniformisation and loss of biodiversity. **Hedges** serve as windbreaks, as well as habitats and shelters for wildlife, and particularly organisms that are beneficial to crops. In general, a heterogeneity of vegetation (crops, trees and green cover) helps restore a richer biodiversity on the parcel of land, but little research has been conducted to quantify these effects.

Finally, agroforestry would represent a method of adaptation to climate change, by protecting crops against weather extremes (in particular early thermal stress in springtime). Competition for water between trees and the crop could be increased in the event of more frequent or more severe droughts, but the technical choices explored (low tree density, soils with a high UR) minimise this risk.

• Conclusions

The availability of data (fragmented data) is a real obstacle to the calculation of the unitary abatement potential of this measure. Furthermore, calculation of a realistic technical potential applicability is difficult for a measure involving highly innovative farming practices, for which both the acceptability criteria and the economic results are unknown. This situation made it necessary to make numerous hypotheses, weakening the calculations.

For **agroforestry**, which remains little developed across the country, the unitary storage values proposed are cautious, the technical potential applicability was assessed in a realistic manner and the adoption rates are reasonable given the highly innovative nature of this practice; this leads us to consider that the global result is plausible and authorises comparison with the other measures studied. The analysis demonstrates that it is possible to introduce trees into agricultural fields while maintaining French agricultural output, and to store carbon in soil and biomass.

Beyond the uncertainties related to its economic results, agroforestry represents an interesting alternative to other options (afforestation of farmland, for example) to contribute to carbon storage, despite the fact that its development is necessarily limited due to the agricultural production losses it induces. In addition, these simple profitability calculations do not take into account opportunity costs, which are high insofar as this measure involves a long-term investment in an uncertain future.

As regards the **hedges** sub-measure, this is a practice already implemented on a national scale, with a very significant scope. Nonetheless, the references regarding additional storage potential following the planting of hedges demonstrate a high level of variability in terms of both space and time. This led to a relatively modest unitary abatement potential being chosen. The development potential therefore appears to be significant and the 10% scenario for the maximum technical potential applicability in 2030 is realistic; the 20% scenario is considered to be optimistic. That lea-ves the question of the relatively high cost of planting and maintain-ning hedges, which can constitute an obstacle to their introduction. In this study, we considered use of the wood as construction timber for agroforestry and shredding and chipping of wood from hedges, corresponding to plausible but debatable hypotheses.

The measure modifies agricultural production, but its MTPA (10% of the theoretical potential applicability) is low compared to that of the other measures. These calculations only concern low-density plantations. Medium and high-density plantations - not considered for this measure - may lead, at the end of the period, to significant falls in agricultural production, or may even halt it altogether.

↘ CO_2

↘N_2O

6 Optimise grassland management to promote carbon storage and reduce N_2O emissions

A. Extend the grazing period
B. Increase the lifespan of temporary sown grassland
C. Reduce fertiliser application on the most intensive permanent and temporary sown grassland
D. Improve low productive permanent grassland by increasing livestock density

I- Challenge and principle of the measure

Grassland is central to the environmental debate due to its contribution to the multi-functionality of livestock farms and its positive effect on environmental impacts. However, its existence greatly depends on livestock production since these areas are usually maintained for forage production and grazing. Recent studies have shown that grassland constitutes carbon (C) sinks able to partially compensate for the GHG emissions of the livestock farming sector, which represent about 9% of total French GHG emissions. However, the extent of this additional C storage of grassland and, more globally, the contribution of grassland to GHG balance, mainly depends on the type (permanent or temporary grassland) and the agricultural practices (i.e. grazing and/or mowing, livestock density, level of fertiliser application, etc.).

The measure is aimed at modifying agricultural practices applied to grassland in order to improve its GHG balance; this measure does not foresee an increase in grassland areas, and a subsequent change in land use, Four options linked to optimisation of grassland management affecting both C storage and N_2O emissions, were analysed: extending the grazing period, increasing the lifespan of temporary sown grassland, "de-intensification" of fertilised grassland and moderate intensification of unproductive grassland.

II- Mechanisms involved and technical methods of the measure

Grassland management significantly affects: 1) C storage in the soil, 2) N_2O emissions linked to mineral nitrogen fertiliser application and manure management, 3) CO_2 emissions due to fossil fuel consumption during farming operations and 4) CH_4 emissions linked to enteric fermentation and manure management.

• Grassland management and carbon storage

In grassland, carbon accumulates mainly as soil organic matter in the first 30 cm of the soil profile, where soil C stocks depend on soil texture, climate conditions and land use history, as well as the age and plant species composition of the vegetation cover. Key factors to provide and maintain carbon sequestration are plant biomass production (level of primary production), organic returns (grazing herd droppings or manure spreading), as well as soil disturbances (i.e. tillage), which accelerate the mineralisation of organic matter, leading to carbon release.

The grassland management practices having an impact on C storage are:
- the type of grassland use: i) grazing increases C sequestration through direct return, via droppings, of undigested carbon and nitrogen from livestock; ii) for mowing (carbon exports are not generally offset by the supply of exogenous organic matter);
- the intensity of use; number of cuts or livestock density (i.e. number of animals per area unit), determines the C export of biomass on the one hand, and stimulates vegetation production in the case of nutrient-poor grasslands;
- the level of fertilisation, either mineral (synthetic fertilisers) and/or organic (livestock droppings, manure/slurry) ;
- the frequency of grassland tillage (by ploughing), which destroys the vegetation cover and leads to accelerated decomposition of soil organic matter: ploughing of permanent grassland (PG) can release 6.2 to 11 t of CO_2e per hectare and year during the first years; carbon losses are high for young (<5yrs) temporary sown grassland.

• Grassland management and N_2O and CH_4 emissions

N_2O emissions, both direct (occurring on site) and indirect (related to leaching of nitrate and volatilised forms of ammonia) are mainly linked to mineral and organic fertiliser application as well as animal excreta. These emissions are particularly high if the nitrogen supplied exceeds the absorption capacities of the vegetation; recent studies suggest that fertiliser applications often exceed effective amounts by a quarter. Reducing the amount of nitrogen applied therefore reduces direct and indirect N_2O emissions. Concerning, N_2O emissions from livestock droppings; changing diet and animal stocking density significantly affects the amounts of nitrogen excreted and hence N_2O emissions.

CH_4 emissions produced as a result of enteric fermentation are mainly affected by diet; a grass-based diet is likely to reduce emissions. Emissions produced via fermentation of droppings are greater under anaerobic conditions and, thus, higher inside buildings and during manure storage compared to those during grazing.

Grazing is likely to increase N_2O emissions due to soil compaction via livestock trampling and standing, leading to more anaerobic conditions. As for droppings, higher N_2O emissions will be found when soil is wet (i.e. less favourable moisture and temperature conditions) than when manure is spread in selected conditions. However, compared to indoor consumption of harvested grass, grazing avoids N_2O and CH_4 emissions associated with manure-management in buildings and spreading. Livestock density also has a direct and indirect effect on N_2O and CH_4 emissions from enteric fermentation and animal droppings.

Ploughing the grassland converts organic nitrogen into mineral nitrogen - a source of direct and indirect N_2O emissions - by accelerating the decomposition of organic matter in the soil.

Recent studies show that non-intensive livestock farming practices increase C storage while reducing GHG emissions from the soil (N_2O from surplus nitrogen) and livestock (CH_4). However, in very extensive grassland areas, C storage may be limited by the low primary productivity of the system. Here an increase to moderate grazing practices will lead to better C storage than mowing, due to return of above-ground litter (unconsumed plant tissues), which increase nutrient cycling.

• The sub-measures studied

A. Extend the grazing period. The sub-measure consists in extending the grazing period by approximately twenty days, putting cows out onto grass earlier in the spring and bringing them back in later in the autumn, respectively. The main effect of this measure is an increase in droppings on the pasture instead of in the barn, leading to lower CH_4 and N_2O emissions compared to those produced indoors and subsequent spreading. The sub-measure is based on the fact that grazed grasslands are often underused and can be applied without an increase in grassland area since it makes use of a biomass that is generally ignored; it modifies the diet and hence the GHG emissions of livestock.

B. Increase the lifespan of temporary sown grassland (TG). This sub-measure aims to reduce the frequency of ploughing of temporary sown grasslands, in order to increase the period of C storage and reduce CO_2 and N_2O emissions related to ploughing. The reduction in soil tillage also reduces emissions related to diesel consumption. This sub-measure does not involve any increase in TG area.

C. "De-intensification" of intensively fertilised permanent and temporary grassland. The aim is to decrease N_2O emissions from fertilisation by reducing mineral nitrogen applications. This reduction in applications - by 10 to 14% on average - is differentiated depending on the current fertilisation level. It should have little impact on grass production insofar as current nitrogen applications to grassland are often excessive.

D. Moderate intensification of permanent unproductive grassland (i.e. rough grazing, alpine grazing, moorland). The aim is to increase C storage by stimulating the primary production of vegetation, often limited by nutrient deficiency. A moderate increase in herbage use will accelerate carbon and nitrogen cycling though animal droppings. This intensification can be achieved by increasing the livestock density by 20%.

• Other effects of the measure on GHGs

Some changes in grassland management (level of fertilisation, tillage frequency, grazing and mowing, manure management) have repercussions on the consumption of other GHG-emitting inputs on farm level such as:

- direct CO_2 emissions, from the combustion of fossil fuels used by farm machinery (for hay or silage-making, tillage, manure spreading);

- "induced" emissions of CO_2 and/or N_2O related to the production and transport of mineral nitrogen fertilisers, fuel and bought-in concentrated feed (soybean, in particular).

III- Calculations of the abatement potential and cost of the measures

• Systems and calculation methods used

One of the main calculation difficulties is related to a lack of regionalised references concerning the effects of grassland management (impacts on vegetation, C storage, etc.) and the absence of statistical data relative to grassland use and management (proportion of surface areas grazed by cows and type of cows, etc.), and the diet of livestock (number of grazing dairy cows, etc.). To overcome this problem hypotheses have to be made, the relevance of which is sometimes difficult to verify.

The statistical sources used are the 2010 Annual farming statistics (SAA) database (for cattle numbers and the areas of the different grassland categories) and the 2006 "Cropping Practices" survey (for fertilisation levels and age of TG).

The management methods adopted to perform the calculations are as follows.

Sub-measure A. Extension of the grazing period by 20 days is applied to grassland used for dairy cows and mixed dairy/beef herds, on lowland farms with a main forage area (MFA) including over 10% maize; more grassland-based systems are excluded since they often already make maximum use of grazing possibilities.
To determine effects on the nutrition system and the GHG emissions of the animals and their droppings, the increase in grazing period was applied to the standard feed rations described by the Observatoire de l'alimentation des vaches laitières (Dairy cow diet observatory) of the Institut de l'élevage (French Livestock Institute) (method also used in Measure 7). The modified feed rations of the extended grazing period were then re-calculated using the CowNex method, making it possible to estimate the savings made for other feed (100-200 kg maize and grass silage and 20-40 kg of soybean per cow) as well as the increase in the proportion of droppings excreted outdoors.

Sub-measure B. The method selected involves increasing the lifespan of temporary grassland by 5 years. This was applied to: 100% of 4 year-old temporary grassland (in 2010), 80% of 3 year-old TG, 65% of 2 year-old TGs and 50% of one-year old grassland. The extension of lifespan is assumed without any reduction in productivity.

Sub-measure C. Nitrogen fertiliser application is reduced by 25% for grassland receiving >150 kgN/ha, by 15% for fertilisation of 100 to 150 kgN/ha, by 10% for fertilisation of 50 to 100 kgN/ha and by 5% for fertilisation <50 kgN/ha.

Sub-measure D. A moderate intensification in unproductive grassland by increasing livestock density by 20%, assuming that cattle are transferred from a nearby paddock. The herbage mass saved in this way is assumed to be available for mowing. Due to the absence of statistical data concerning the use of these unproductive grassland areas, an initial livestock density of 0.2 LSU/ha and 100 day grazing period per year was applied for this measure.

• Effects of the measure on GHGs and calculation of its unitary abatement potential

The unitary abatements are calculated using the "CITEPA" method (i.e. 1996 IPCC recommendations), and an "expert" method, respectively:
- for C storage and direct CO_2, CH_4 and N_2O emissions: the new coefficients adopted by the IPCC (in 2006);
- for indirect N_2O emissions on grazing (measure A)the EMEP/EEA method (see Measure 8), enabling better incorporation of the various forms of nitrogen excretion (i.e. ammonia).
All the calculations were carried out per region in order to take into account the geographic diversity of soil C stocks, mineral fertiliser applications and diets of cows. The results were then aggregated on a national level.

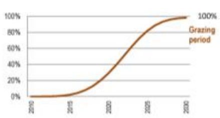
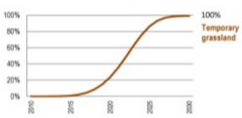
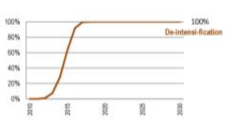
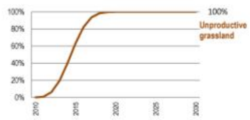
	Sub-measures	A. Grazing period	B. Lifespan of temporary grassland	C. De-intensification	D. Unproductive grassland
Technical content	Initial situation	Grazing season often under using the available herbage mass	Lifespan of temporary sown grassland (TG) is 1 to 5 years, with 65% of TG < 3 years	Excessive nitrogen fertiliser application	Low C storage due to low primary production. Hypoth.: livestock density of 0.2 LSU/ha, 100 days of grazing (e.g. alpine grazing)
	Change in management	Extension of the grazing season by 20 days →modification in diet, location of droppings and quantity of manure to be spread	Increase in the lifespan to 5 years	Reduction in mineral fertiliser applications, particularly significant given the high current dose	20% increase in livestock density (0.24 LSU/ha), saving (elsewhere) 37 kg of dry matter (harvestable as hay)
Unitary abatement potential	**C storage** $kgCO_2e/ha/year$	-	↘ in carbon release due to less frequent tillage: 520	-	↗ in storage due to stimulation in primary production: 1,416
	N_2O emissions (direct + indirect)	↘ in emissions related to manure storage and spreading: 22	↘ in emissions related to mineralisation of organic matter: 54	↘ in emissions related to reduced fertiliser application: 52	↗ in N_2O and NH_3 from urine related to ↗ in animal density: -7
	Direct CO_2 emissions	↘in fuel consumption: 6	↘in fuel consumption: 38	-	↗in fuel consumption: -447
	CH_4 emissions(enteric fermentation and droppings)	↘ in enteric fermentation and droppings: 22	-	-	↗ in enteric fermentation and droppings related to livestock density: -22
	Total direct + indirect emissions	**50** $kgCO_2e/ha/year$ [62 $kgCO_2e$/dairy cow/year]	**612**	**52**	**940**
	Induced CO_2 and N_2O emissions (upstream)	↘ in fuel (harvesting of grass, manure spreading), ↘ in imported soybean: 3 $kgCO_2/ha/year$; 4$kgCO_2$/dairy cow/year	↘ in fuel (due to↘ in ploughing): 8	↘ in mineral fertilisers: 48	↗ fuel: -90
	Total $kgCO_2e/ha/year$	**53** [66 $kgCO_2e$/dairy cow/year]	**620**	**100**	**850**
Unitary cost	**Modification in consumption**	↘ in mowing/silage-making operations ↘ in concentrated feed consumption ↘ inmanure-spreading cost: -€11/ha, -€13/dairy cow	↘ in soil tillage and sowing (soil preparation, seed): €112/ha	↘ in fertiliser: -€8/ha	↗ Harvesting of spared biomass as hay (€36/DMT) : €1.3
	Modification in production	↘ in milk production during the winter period: -€0.90/ha, -€1.14/dairy cow Saving in silage maize → sale of silage maize: -€15/ha; -€18 /dairy cow	-	-	Sale of hay (€144/DMT): €5.3
	Total €/ha	-€26/ha (-30 to -15) [-€32/dairy cow (-37 to -20)]	-€112/ha (-121 to -103)	-€8/ha (-11 to -6)	-€4/ha (-4 to -2)
Potential applicability	**Theoretical pot. applicability**	Grazed grassland: 10.8 Mha 3.7 M head	Temporary sown grassland: 2.6 Mha	All grassland	Unproductive grassland: 2.5 Mha
	Technical criteria	Grassland grazed by dairy cows or mixed dairy/beef herds Exclusion of farms where maize <10% of the MFA	Exclusion of TG ≥ 5 years, and 40% of TG in rotation with maize (0.4 Mha)	Grassland receiving mineral fertiliser	Grassland located close to other grazing land, assumption that this is the case for 20% of this grassland
	Max. Technical Pot. Applicability (MTPA)	4.0 Mha (i.e. 37% of grazed areas). 3.14 M head	1.8 Mha	8.9 Mha, including 2.4 Mha of TG and 6.4 Mha of PG	0.5 Mha
Adoption scenario	**2010 reference situation**	0%	0%	0%	0%
	Adoption scenario	98.5% of MTPA in 2030 	99% of MTPA in 2030 	100% of MTPA in 2030 	100% of MTPA in 2030 

Table 2

Target effects:

. The increase in C storage, which may result from extension of the storage period (delayed ploughing up of grassland), for sub-measure B, or an increase in primary production, for D. The additional storage and carbon release induced by ploughing are calculated according grassland age (measure B) and management changes (measure D) by varying emission factors.

. The reduction in N_2O emissions (direct and indirect) related to fertiliser supply (measure (C) and manure management (measures A, D), which differ depending on whether droppings are produced on grazing land, indoors or spread as manure. For A, the indirect emissions are calculated using the EMEP/EEA method, which provides more precise emission factors for ammonia.

. The reduction in CH_4 emissions related to enteric fermentation (measure A and D) or fermentation of manure; which are lower on grassland than indoors and when spread. These emissions are calculated according to IPCC guidelines (in 2006) and depending on the animal weight and diet during grazing and housing.

Other effects quantified:

. The modification in direct CO2 emissions related to farm operations and the use of agricultural machinery, such as reduction or increase in grass harvesting operations (measures A and D), reduction in manure spreading (measure A) and soil tillage (measure B). These emissions are calculated using data from the Dia'terre® - Ges'tim database.

. A reduction in induced emissions (i.e. farm gate emissions upstream of the farm), related to the production and transport of fuels (all sub-measures), mineral nitrogen fertilisers (measure C) and imported feed (measure A: soybean). These emissions are calculated using the Carbone® database.

• Estimation of the unitary cost for the farmer

The costs/savings include:
- input savings, related to a reduction in fertilisation (measure C) and concentrated feed purchases due to additional grazing (measure A);
- farm operations: reduced mowing or silage-making due to grazing of herbage mass; A) or additional mowing and silage-making due to saved herbage mass which is no longer grazed ; measure D); less frequent ploughing and sowing of TG (B);
- sales of maize (measure A) or hay (measure D) resulting from the forage not consumed due to an extended grazing period and area;
- loss of milk production during the winter period due to a grass-based diet (A).

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

The t criteria used to determine the maximum area the sub-measures can be applied to relate to: the grassland attributed to livestock farming systems (measure A: grazing by dairy cows and mixed dairy/beef herds, in systems using silage maize); the age of temporary sown grassland and related crop rotations (B); the quantity of mineral fertilisation (C) and the location of unproductive grassland (D: location close to other grazing on the same farm, enabling the transfer of a few animals).

Measure adoption scenario

Since all sub-measures are economically interesting for farmers and relatively easy to implement, application to the entire MTPA was estimated for 2030 for sub-measures A, B and C, and by 2020 for D.

IV- Results and their context

		Units	Year 2030					Cumulative value over the period 2010-2030			
			A	B	C	D	**Total**	A	B	C	D
Abatement potential, "CITEPA" calculation (without induced emissions)		$MtCO_2e$	0.1	0.09 (a)	0.7	0.5	**1.3**	0.9	0.18 (a)	12.2	7.0
Abatement potential, "expert" calculation	Without induced emissions	$MtCO_2e$	0.2 (0.1 to 0.2)	1.44 (0.5 to 1.2)	0.5 (0.2 to 0.9)	0.5 (0.3 to 1.5)	**2.5 (1.1 to 3.6)**	1.5 (0 to 0.2)	13.9 (9.8 to 28.0)	7.6 (3.5 to 14.5)	7.3 (4.4 to 21.0)
	With induced emissions	$MtCO_2e$	0.2 (0.1 to 0.2)	1.5 (0.5 to 1.6)	0.9 (0.6 to 1.3)	0.4 (0.2 to 1.3)	**3.0 (1.5 to 4.0)**	1.6 (0.1 to 0.3)	14.0 (10.0 to 28.1)	14.6 (10.5 to 21.6)	6.5 (3.7 to 20.3)
Total cost for farmers		€M	-101 (-118 to -61)	-265 (-285 to -243)	-70 (-99 to -48)	-1.9 (-2 to -1)	**-437 (-504 to -353)**	-789 (-922 to -474)	-2546 (-2742 to -2338)	-1150 (-1625 to -783)	-31 (-33 to -16)
Cost per metric ton of CO_2e for the farmer ("expert" calculation, without induced emissions)		€/tCO_2e	-515	-184	-152	-4	**-172**	-	-	-	-

(a) only taking into account fuel
M: million

Table 2

•The results

All the sub-measures have a negative cost (a gain). As regards the gains per ton of CO_2e avoided, the most interesting sub-measures are: extending the grazing period (A), increasing the lifespan of TG (B) and "de-intensification" of grassland (C).

Concerning the emissions abatements (excluding induced emissions) of the MTPA and the period 2010-2030, the most interesting sub-measures are increasing the lifespan of TG (B), followed by de-intensification (C) and intensification (D).

Comparison with the results of other equivalent studies (Ireland, UK, etc.) confirms these results concerning extending the annual grazing period, de-intensification of fertilised grasslands (C) and increasing the lifespan of TG (B).

• The sensitivity of the results to the hypotheses

In the case of N_2O emissions, there is a marked difference between the two calculation methods used.

In addition, several major assumptions, with a significant impact on the results, had to be made concerning the current and potential use of grass, as well as its impacts on other components of the system.

Sub-measure A assumes that the lowland farms targeted under-use grazing and use more silage maize, grass silage and soybean meal than necessary, which is not always the case. It then assumes that additional grazing generates savings in silage maize, allowing grain maize to be produced in its place - in relatively favourable yield and sales price conditions. The indoor feed savings (€12.5 /dairy cow) calculated on this basis represent 40% of the unitary gain of the sub-measure.

For sub-measures B and C, we hypothesised that an increase in TG lifespan and a reduction in mineral fertiliser application do not lead to a reduction in yield; yet a reduction would have a marked economic impact (use of forage or bought-in concentrated feed, reduction in animal production, etc.).

Sub-measure D assumes that the transfer of livestock from a productive to an unproductive paddock frees up additional herbage mass in the productive paddock, which can be used to produce hay; this production is estimated on the basis of favourable hypotheses (relating to yield, harvesting cost, sales price and accessibility of plots).

However, the calculations made with lower and upper values for a variety of variables do not affect the magnitudes of the unitary gains for the farmer, or the "costs" (negative) per metric ton of CO_2e avoided.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effect

The current CITEPA inventory does not take into account changes in the C stores of grassland. However, a tier 1 calculation method (IPCC 2006) method exists taking into account agronomic and soil and climate conditions that France could potentially use, and the method developed here could serve as the basis for a tier 2 calculation.

The improvement in GHG balance related to an increase in grazing period does not emerge with the current CITEPA method since N_2O gas emissions on grazing land are considered to be as high as for the indoor housing-storage-manure spreading sequence. However, the EMEP/EEA method used to more accurately calculate indirect N_2O emissions demonstrates a significant effect (reduction) of extending the grazing period.

Verifiability of implementation

Changes in grassland management are difficult to identify - and even more difficult to verify - as are the majority of changes in management practices. Only the lifespans of temporary grassland are included in annual farming statistics. Statistical data concerning grassland use methods are absent: the five-year "Cropping Practices" survey does not specify grazing methods (type of livestock and stocking density) and does not record permanent grassland.

• The contexts and measures liable to promote the roll-out of the measure

For the past 30 years, despite support measures such as the grassland premium (since 1993), there has been a steady decrease in grassland surface areas (12.8 Mha in 1980 compared to 7.4 Mha in 2010), replaced by silage maize and cereals (i.e. cultivated areas emitting more GHGs). A reduction in the ploughing frequency of TG and in fertiliser use could be encouraged by market recognition of quality (environmental label, protected designation of origin, etc.).

• Other effects of the measure

Grassland areas contribute to the multi-functionality of livestock farms (biodiversity, landscape aesthetics) and help reduce their environmental impacts (water quality, etc.).

Extending the grazing period reduces the amount of manure produced indoors and hence available for methanisation or spreading on areas where it is liable to be replaced by mineral fertilisers.

• Vulnerability and adaptability of the measure to climate change

Climate change (extreme events) and changes in land use are liable to have a marked effect on C storage on grassland due to an acceleration in the decomposition of organic matter in the soil (following ploughing, high temperatures).

•Conclusions

All the sub-measures examined are "win-win" (the practices proposed to improve the GHG balance are also economically beneficial) and appear to be easy to implement. However, the fact that they are not adopted by farmers yet implies the existence of obstacles.

Sub-measure A: The requirement to put livestock outside during the day during periods when weather conditions are still unpredictable can be seen as an obstacle. However, spring grazing may regulate grass growth and generates silage and oilcake savings. This practice leads to low GHG savings but the gain per metric ton of CO_2e appears to be very high.

Sub-measures B and C: The risk of a slight reduction in yields and forage stocks may dissuade farmers from implementing these measures. However, the significant potential for financial and GHG savings appear to be an advantage that may compensate for a possible reduction in yield.

Sub-measure D: Although this measure appears to be easy to implement, the low economic gain for farmers and the additional work required (moving of livestock and mowing) may appear to be an obstacle.

7 Replace carbohydrates with unsaturated fats and use an additive in the diet of ruminants to reduce enteric CH_4 emissions

↘ CH_4

A. Replace carbohydrates with unsaturated fats in diets
B. Incorporate an additive (nitrate-based) in diets

I- Challenge and principle of the measure

Enteric methane (CH_4) emissions (produced almost exclusively by ruminants) represented 29 million metric tons of CO_2 equivalent ($MtCO_2e$) in 2010, i.e. 27% of GHG emissions from the agricultural sector and 5% of all French emissions.

The digestion of carbohydrates in the rumen is accompanied by the production of dihydrogen (H_2), which is transformed into CH_4 by methanogenic microorganisms. It is possible to re-orient rumen function towards metabolic pathways that produce less methane via limited changes to the animals' diet.

The measure examines two ways of modifying feed rations: (A) the addition of fats (in place of some of the carbohydrates) or (B) a nitrate-based additive. These techniques are only applied to livestock whose feed rations can be easily modified by the farmer (fed at least partially indoors). Only cattle are targeted, since other ruminants - sheep and goats - account for just 7% of French enteric emissions.

II- Mechanisms and technical methods of the measure

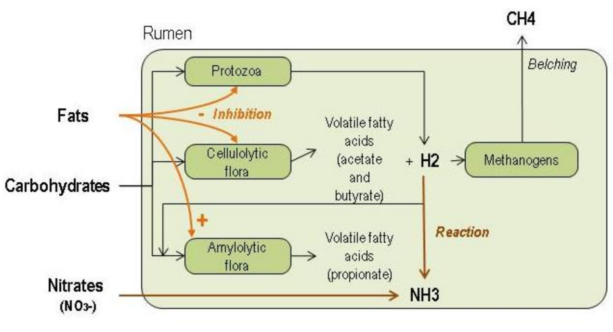
The emission of CH_4 corresponds to the elimination of the H_2 produced in the rumen by the breaking down of carbohydrates; it can be reduced via lower H_2 production or the elimination of this H_2 in a form other than CH_4. These effects can be obtained, respectively, by incorporating fats or an additive into the feed rations (Figure). These dietary changes must adhere to certain rules.

• The sub-measures studied

The addition of fats

Various whole oils and oilseeds (raw or extruded) can be used as fat sources; some have specific fatty acid compositions considered to be of nutritional value to consumers (high omega 3 unsaturated fat content, in particular). The incorporation of fats is restricted by nutritional limits (too many fats can reduce the digestibility of cellulose and cause an excessive modification in the fatty acid composition of products), technological constraints (maximum oil incorporation level in concentrated feeds) and by practical considerations for distribution to livestock (easy-to-handle extruded products). When selecting fat sources, it is necessary to favour those that are the least expensive to farmers (oilseed rape) and take into account their current or potential availability (linseed crops offer good development probabilities). The partial use of linseed (which has a high omega-3 content) is adopted, although this is more expensive than oilseed rape. The dry matter in the modified diet is fortified with 3 to 3.5% unsaturated fats, depending on the animal categories (lower content for animals receiving little concentrated feed).

Rumen function and modifications induced by the addition of fats or nitrate to feed rations



The fermentation of carbohydrates by cellulolytic flora and protozoa produces H_2, whereas fermentation by amylolytic flora uses it. The remaining H_2 is converted into CH_4 by methanogenic substances.
A. Cellulolytic bacteria and protozoa populations are reduced by the presence of **unsaturated fats**, reducing the production of H_2 and promoting its use in the biochemical pathways favoured by amylolytic flora.
B. Some of the H_2 is converted into NH_3 by reacting with the **nitrate**, limiting its availability and hence the production of CH_4.

The addition of an additive

This additive must have a long-term effect that has been demonstrated *in vivo*. The only additive to have done so to date is nitrate, which absorbs the H_2 produced. *In vivo* experiments have validated doses of 1.7 to 2.6% nitrate in the feed rations. Since too much nitrate can be toxic for animals (accumulation of nitrites), it is essential to limit the risks of overdose and hence for the additive to be incorporated into compound feeds by the animal nutrition industry. Since the addition must not lead to nitrogen losses, it is necessary to substitute nitrate for urea or a proportion of the oilcake ration in diets with a low fermentable nitrogen content (i.e. those based on silage maize). The hypothesis adopted is a diet modified by the addition of 1% nitrate.

At present, no published *in vivo* trials have combined the use of unsaturated fats with nitrate. To our knowledge, trials of this type are underway, but the results will only be available at mid-2014. The 2 sub-measures are theoretically cumulative since they involve independent processes.

• Other effects of the measure on GHGs

The substitution of ingredients in the feed rations (sub-measure A) modifies the demand for agricultural raw materials, either produced in France (oil crops and cereals) or imported (soybean meal) and therefore has repercussions on "induced" GHG emissions (upstream of the farm).

This abatement lever has no effect on the "Reduce the amount of protein in the diet of livestock to limit the quantity of nitrogen excreted in manure and the associated N_2O emissions" measure since it does not significantly modify the quantities of nitrogen excreted in the droppings.

III- Calculations of the abatement potential and cost of the measures

• Systems and calculation methods used

All the calculations are performed with differentiation between cattle categories (15 categories taken from the Annual farming statistics (SAA) database nomenclature), sub-divided on the basis of the amount of concentrates received by the animals (on the basis of the feed ration typology developed by the Observatoire de l'alimentation des vaches laitières (Dairy cow diet observatory) of the Institut de l'élevage (Institute of Animal Husbandry)). The cattle numbers are taken from the 2010 Annual farming statistics (SAA) database.

The CITEPA calculation method for 2010 emissions is based on application of emission factors adapted to the characteristics of French livestock farming (i.e. specific to each category of animals), but which cannot take into account the effects of changes in feed rations. An "expert" calculation method, founded on data from the scientific literature, is proposed: correction coefficients are applied to the emissions calculated using the CITEPA method, on the basis of the quantity of fats or nitrate ingested.

• Effects of the measure on GHGs and calculation of its unitary abatement potential

Target effect:

. **The reduction in CH_4 emissions** resulting from enteric fermentation. This is estimated by calculating the emissions with the "CITEPA" method, then correcting them using the coefficient taking into account the modified diet, for the days of the year when the concentrated feed is actually distributed at a dose of more than 1 kg/d.

Other effect quantified:

. **The modification in induced emissions**, related to substitution of agricultural raw materials in the feed rations. This is calculated by quantifying the changes in GHG emissions due to the fact that the production of oil crops and cereal crops does not result in the same emissions. The calculation is based on standard LCA data provided by the Dia'terre® - Ges'tim database for cereals and oilcakes, or on INRA data for oil crops (not recorded in the Dia'terre® - Ges'tim database). An emission factor aggregating the different effects is assigned to each feed, and the calculations take into account the number of days when the concentrate is given (2 months of dry period for cows, for example)

Effects ignored:

- The possible effects on **manure fermentation** (↗ CH_4) **and nitrogen released** (↗ N_2O). By reducing the digestibility of carbohydrates, fats may increase the amount of undigested organic matter and hence the amount of CH_4 produced by fermentation of droppings: these effects are not clear but limited by the hypotheses adopted for the composition of modified feed rations. For sub-measure B, the hypothesis adopted, according to which the addition of nitrate is offset by a reduction in urea content, leads to a limited effect on the amount of fermentable nitrogen in the rumen and hence on nitrogen losses via the urine.

- The energy consumption (CO_2 emitting) associated with the manufacture of the additive (calcium and ammonium nitrate) is ignored since it replaces the production of urea.

• Estimation of the unitary cost for the farmer

This is the cost associated with changing the composition of the feed rations; the distribution method is identical and thus involves no additional equipment or labour costs for farmers.

Feed substitution: the cost of substituting a proportion of the carbohydrates in the feed rations with fats is calculated on the basis of 2010 oilseed and oil prices. It should be noted that agricultural raw material prices have become highly volatile, however.

Additive purchase: since the product is not currently marketed, a price hypothesis was determined for the study: the addition of nitrate is accompanied by a reduction in the amount of urea purchased.

Since the technical development (additive) and necessary training of farmers (fats and nitrate) are covered by animal feed companies, no additional cost is to be predicted for farmers.

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

The measure applies to the proportion of the bovine herd for which the feed rations can be modified by farmers, i.e. cattle receiving concentrated feeds indoors. The sub-populations identified for the 2 sub-measures are: the majority of the dairy herd and a proportion of the suckling herd for the first one, and a proportion of dairy cows and young bulls form dairy and suckling herds for the second one.

Measure adoption scenario

For **fats**, no obstacles to the adoption of the technique were identified (no segment of the milk or meat market prohibits the use of the fat sources selected for this measure). The accessibility of the ingredients is not a limiting factor: in the event that one of the fat sources is unavailable (oilseed rape, soybean or linseed), the use of other raw materials is still possible. The hypothesis adopted is therefore that the maximum would be reached by 2022.

For **nitrate**, however, the adoption rate and maximum are limited:

- the technique is only considered to be applicable from 2015 (availability of additives). It should be noted that a proportion of the technique to be implemented is protected by a patent, which may constitute a limitation for feed manufacturers.
- the acceptability of the method could be poor ("industrial" technique, negative connotation of the word "nitrate", risk of accidents due to overdosing), acting as an obstacle to its adoption by farmers and tendering the technique unacceptable in certain production specifications (organic agriculture, protected designation of origin, etc.).

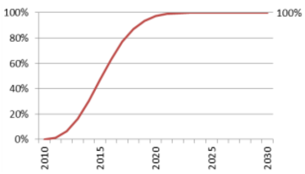
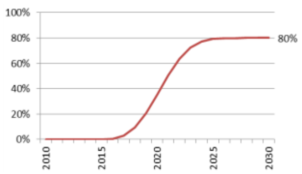
	Sub-measures	A. Carbohydrate/fat substitution	B. Addition of nitrate in feed rations
Technical content of the measure	**Initial situation**	The reference average feed ration contains **1.5% fatty acids in dry matter** and does not contain **nitrate in additive form**. The reference and modified feed rations are considered by animal category	
	Change in feed ration	The modified feed ration contains **4.5 to 5% fatty acids in dry matter** (+3 to 3.5% compared to the reference) Two technical options coupled together in the calculations: Extruded oilseeds in place of carbohydrates (50% linseed, 50% oilseed rape); to supplement if necessary: Oils incorporated in a concentrated feed (50% soybean, 50% oilseed rape)	The modified feed ration contains **1% nitrate** (in the form of calcium nitrate). **!** A significant overdose represents a health risk to animals; a smaller overdose increases nitrogen losses in the urine. It is essential that the feed be produced by manufacturers to prevent overdosing.
Unitary abatement potential	**CH_4 emissions** (enteric fermentation)	"CITEPA" method The modification in feed rations has no effect on the value of the emission factors used at present in CITEPA calculations. "**Expert**" method: Calculation of the emissions abatement for each animal category:	
		-14% CH_4 for +3.5% fats in feed rations (-4% for +1% fats)	**-10% CH_4 for 1% nitrate in feed rations**
	Direct + indirect total kgCO2e/animal/year	Dairy cows: **401** Suckling cows and young bulls aged 1 to 2 years: **240 to 320** Other categories: **<240**	Dairy cows: **289** Young bulls: **203**
	Induced CO_2 emissions (upstream)	Change in composition of feed rations ▲ *Values much lower with INRA data than with Dia'terre® - Ges'tim data*	
	kgCO2e/animal/year	↗ in emissions Dairy cows: **191** Suckling cows, young bulls aged 1 to 2 years and beef cattle > 2 years: **100 to 130** Other categories: **<130**	no induced emissions
	Total kgCO2e/animal/year	Dairy cows: **210** Suckling cows and young bulls aged 1 to 2 years: **100 to 200** Other categories: **<100**	Dairy cows: **289** Young bulls: **203**
Unitary cost	**Cost of feed rations**	Replacement of some of the carbohydrates in the feed rations with fats	Purchase of nitrate and urea savings
		▲ *Calculation sensitive to the agricultural raw product price hypotheses*	
	Total €/animal/year	Dairy cows: 109 Other animals > 12 months: 47 to 78	Dairy cows: 11.6 Young bulls (dairy herd): 6.8 Young bulls (beef herd): 5.7
Potential applicability	**Theoretical pot. applicability**	**All cattle** (except veal and fattening cattle)**: 18,716,000 animal equivalents**	
	Technical criteria	Animals receiving concentrated feeds indoors Amount of concentrated feeds received > 1 kg/day During the period when they receive the concentrated feed indoors	Animals receiving concentrated feeds indoors Animals with a diet low in fermentable nitrogen (i.e. based on silage maize)
	Max. Technical Pot. Applicability (MTPA)	**All cattle meeting the criteria above**, on a prorata basis according to the duration of period for which their feed rations are modified, i.e. **6,595,000 animal equivalents**	**3,469,000 cattle:** 2,990,000 dairy cows 200,000 young bulls from dairy herds 279,000 young bulls from beef herds
Adoption scenario	**2010 reference situation**	5% of dairy cows receive feed fortified with fats (case of high-producing animals)	No cows receive nitrate in their feed
	Adoption scenario	Hypotheses: No adoption obstacles →100% of the MTPA reached by 2022 	Hypotheses: additive assumed to be available in 2015 only (on condition that an MA is obtained) and adoption obstacles →80% of the MTPA reached by 2030 

Table 1

IV- Results and their context

		units (M: million)	Year 2030			Cumulative value over the period 2010-2030	
			Fats	Nitrate	**Total 2 sub-measures**	Fats	Nitrate
Abatement potential* ("CITEPA" method) Without induced emissions		MtCO2e	0	0	**0**	0	0
Abatement potential* ("expert" method)	Without induced emissions	MtCO2e	1.9 (1.5 to 2.3)	0.5 (0.4 to 0.9)	**2.4 (1.9 to 3.1)**	27.0 (21.6 to 32.4)	4.5 (3.6 to 8.0)
	With induced emissions	MtCO2e	1.0 (0.7 to 1.4)	0.5 (0.4 to 0.9)	**1.5 (1.0 to 2.3)**	14.7 (9.3 to 20.1)	4.5 (3.6 to 8.0)
Total cost for farmers		€M	505.9	18.4 (18.4 to 27.6)	**524.3 (524.3 to 533.5)**	7209.2	170.1 (170.1 to 255.1)
Cost per metric ton of CO_2e for the farmer ("expert" method, without induced emissions)		€/tCO_2e	267 (223 to 335)	38 (32 to 48)	**221**	-	-

* The abatement potential is given with upper and lower values, related to the abatement percentage per unit of fats or nitrate added, and to the nitrate dose added (the fat dose added being constant).

Table 2

• The results

The abatement potential for the measure as a whole is 2.4 MtCO_2e/year in 2030 when fats and nitrate are disseminated to 100% and 80% of the MTPA respectively. However, this abatement is reduced to 1.5 Mt when the effects induced upstream of the farm are taken into account.

This incorporation - or otherwise - of "induced" emissions - i.e. those occurring outside the farm - substantially modifies the abatement potential of the "Fats" sub-measure (potential abatement reduced by almost 50%), whereas the effects induced by the "Nitrate" sub-measure are negligible.

The cost per metric ton of CO_2e for the farmer appears to be particularly high for the "Fats" sub-measure (€267/tCO_2e) compared to the "Nitrate" sub-measure (€38): this is due to the difference in price between cereals (around €200-250/t) and oil crops (over €400/t). The cost of the measure would be reduced by using only oilseed rape, which is less expensive for a similar abatement.

The addition of fats or an additive to the feed rations has not been examined by any of the **other studies** available. The ones conducted in Ireland and the USA do not propose any specific measures for reducing enteric methane. The British study considered this objective but adopted the options of the genetic improvement of productivity and fertility - considered here to be an ongoing practice not requiring any modification - and the use of ionophore antibiotics, which are banned in the EU.

• The sensitivity of the results to the hypotheses

Uncertainties relative to induced emissions:

The level of these emissions strongly depends on the references chosen: the calculations were performed with the Dia'terre® - Ges'tim database values for cereals; using the data published by INRA, the estimation of induced emissions is three times lower.

Induced emissions are highly sensitive to the type of oilseed (greater emissions abatement with oilseed rape than with linseed) and the oilcake that it replaces (emissions abatement much greater when soybean is replaced compared to a mixture of oilcakes).

Sensitivity to the cost of agricultural raw materials:

"Fats" sub-measure: optimisation of the composition of feed rations and its cost are highly dependent on raw material prices. The cost of the measure could therefore be significantly modified by a global rise in prices, as observed in recent years, or a change in prices relative to the various crops (related, for example, to an increased demand for certain grains). However, these price variations have a lower impact than uncertainty with respect to carbon footprints.

"Nitrate" sub-measure: while the hypothesis of a cost per kg of urea varying little in the future appears to be robust, the hypothesis retained for nitrate appears to be open to debate; a lower price for the nitrate source, which would make the addition of fermentable nitrogen to the diet less expensive than with urea, could lead to a financial saving for farmers.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effect

As currently implemented (fixed emissions per animal), the "CITEPA" calculation method cannot take into account the abatement expected as a result of this measure. However, consultation with the CITEPA would make it possible to take it into account for fats at least.

Verifiability of implementation

Implementation could be monitored using data supplied by companies producing fat or nitrate supplements. However, monitoring will only be possible if these manufacturers differentiate between the quantities produced for ruminants and those produced for monogastric animals in the case of fats, and between nitrate as fertiliser and as additive for ruminants.

• The contexts and measures liable to promote the roll-out of the measure

The addition of unsaturated fats - costly for farmers - could be promoted by market recognition of the specific quality of the milk and meat produced (compensation for the improvement in fatty acid composition which would offset the additional cost). An initiative of this type already promotes the incorporation of linseed via a "health" claim (products presenting a high omega 3 fat profile more consistent with current nutritional recommendations).

• Vulnerability and adaptability of the measure to climate change

Theoretically, the implementation of this measure does not depend on climate change and the problem of vulnerability is not relevant for a change in feed ration composition.

• Other effects of the measure

"Fats" sub-measure: the effects on human health are not likely to be negative since the fatty acids selected for the sub-measure have unsaturated chains. There is no known effect on animal health.

"Nitrate" sub-measure: a risk to animal health only exists if the farmer does not adhere to the instructions for use proposed and doubles the dose prescribed or does not adhere to an adaptation period for nitrate distribution.

• Conclusions

Firstly, these results demonstrate the possibility of a significant abatement following the addition of fats, three times greater than that of nitrate in terms of cumulative abatement. Secondly, they show the very high cost of this measure, particularly with respect to nitrate. However, the very high level of sensitivity of the results has to be highlighted - firstly to variations in raw material costs and, secondly, to the carbon footprint estimates related to the production of these raw materials. If nitrate - for which a marketing authorisation has not yet been obtained - is marketed at a reasonable price, and if the method of distribution by incorporation in animal feed is well managed, it could constitute an effective abatement method. To date, no other avenues for the abatement of enteric methane have been retained. It is possible that in a few years' time, an additive or an additive mixture other than nitrate may prove to be effective.

↘ N_2O

8 Reduce the amount of protein in the diet of livestock to limit the quantity of nitrogen excreted in manure and the associated N_2O emissions

A. Reduce the protein content in the diets of dairy cows
B. Reduce the protein content in the diets of pigs and sows

I- Challenge and principle of the measure

N_2O emissions associated with manure management are estimated to represent 5.2 million metric tons of CO_2 equivalent ($MtCO_2e$) for all livestock farms in 2010, i.e. 4.9% of agricultural emissions. These emissions occur indoors, on grassland, during storage and after spreading of manure. They result from the dietary nitrogen not absorbed by the animal, which is excreted in the faeces (in a relatively stable form), but, predominantly, in the urine in the form of urea, which is very unstable and readily volatilised as ammonia (NH_3). This can lead to N_2O emissions following subsequent conversions.

To reduce these emissions, the levels of nitrogen ingested - and hence excreted - can both be reduced, by better tailoring the quantity of proteins supplied to the animals' requirements and improving the quality of these proteins and hence their efficiency of use. The objective of the measure is to implement this strategy with little or no effect on production.

The measure is applied to dairy cows and pigs. These animals receive large quantities of protein foods, for which distribution is easy to control. Other cattle are excluded due to a lack of references regarding feeding practices. Sheep and goats are excluded because their numbers are low. For poultry, practices aimed at reducing nitrogen intake are already implemented or more difficult to apply without a reduction in performance.

II- Mechanisms and technical methods of the measure

Irrespective of the animal species, gaseous nitrogen emissions are mainly proportional to the ammonia nitrogen (NH_4^+) present in manure, itself very closely related to the quantity of urea - the main waste product resulting from the metabolism of nitrogen in animals - excreted. While this quantity of urinary nitrogen is high and varies relatively little in monogastric animals (70-80% of the total nitrogen excreted), it is much more variable in ruminants (30 to 80% of the nitrogen excreted depending on the type of diet). Then, the conversion of NH_4^+ into NH_3 or N_2O depends on the type of building and the manure management method.

• Diet and nitrogen excretion

While increasing the proportion of proteins in the diet generally leads to an improvement in animal performance, the additional protein nitrogen not retained by the animal or the milk is excreted almost entirely in the form of urea. This excretion can be reduced without any loss of production by limiting the crude protein (CP) content of the feed rations while at the same time satisfying the animal's essential amino acid (AA) requirements (since the metabolism does not produce these, they have to be present in the diet). The intake of synthetic industrial AAs in place of soybean meal, adjusted to the animal's requirements, ensures these needs are met.

References are regularly issued by the CORPEN (the French steering committee for environmentally-friendly farming practices) regarding nitrogen excretions for farm animals, adjusted to varying degrees depending on the animals' diet. These references can be used to calculate gaseous nitrogen emissions (NH_3 and N_2O) as well as the quantities of organic nitrogen to be applied.

The case of cattle

In ruminants, the metabolism of nitrogen is complicated by reactions occurring inside the rumen, where microorganisms consume readily degradable proteins, producing NH_4^+, which is then partially reused for the synthesis of microbial proteins. The excess is absorbed by the animal (it has become a toxin at this stage). It is then rapidly transformed into urea by the liver, before being excreted.

Urea excretion can be reduced in two ways:
- by a moderate reduction in CPs (an excessive reduction in proteins may reduce the digestibility of feed rations);
- by using proteins protected against degradation by micro-organisms (tannin-treated oilcake). This creates sub-deficiency of nitrogen degradable in the rumen, leading to lower urea excretion and recycling in the rumen.

The use of synthetic AAs was not retained for cattle because the impact on nitrogen emissions is less than for monogastric animals and because their cost is increased by the need to protect the AAs from degradation in the rumen.

These adjustments in the nitrogen content of the diets are only possible in winter diets, when nitrogen is supplied by protein supplements (soybean meal, in particular) that can be easily modified. This is not the case for diets based on grazed grass or other fresh forages or silages fed indoors, with a high CP content and supplying large (and non-modifiable) quantities of degradable nitrogen[12].

In cows, since the urea content of the milk reflects that of the blood, milk monitoring data can be used to diagnose animals receiving feed rations containing too much nitrogen. The data can also be used to monitor the effect of the measure.

The case of pigs

A number of studies have established the fact that feeding fattening pigs a diet with a lower protein content reduces nitrogen excretion but does not affect daily weight gain or the feed conversion ratio if the energy and essential amino acid contents are maintained.

At present, in farrow-to-finish operations, animals receive just one type of feed throughout their lifetime (monophase feeding) or two types of feeds, each adapted to a development phase (biphase

[12] Some studies therefore recommend the use of maize silage as a substitute for grass in order to reduce N_2O emissions.

feeding). Adjusting the composition of the feed ten times during the animal's life (multiphase) leads to an overall reduction in the quantity of proteins distributed. Replacing proteins with cereals combined with industrial amino acids (such as lysine, for example) adapted to the animal's requirements further reduces the amount of nitrogen consumed. These reductions in ingested nitrogen also reduce its excretion: decreasing the protein content from 20 to 12% can reduce NH_3 emissions by 67% during slurry storage.

• The sub-measures studied

For **cattle**, the sub-measure concerns the diet of dairy cows during the winter period, i.e. mainly a diet based on maize silage: the objective is to reduce the crude protein content to 14% for all cows currently receiving more. The measure modifies the feed rations but has no effect on the roughage/concentrated feed ratio, the time spent indoors/outdoors, or the volume of manure produced.

For **pigs, two technical options** (mutually exclusive since they concern the same animal population) are studied:
- **"**2PAA+": generalisation of biphase feeding, with increased use of industrial AAs in place of soybean meal;
- "MPAA+": development of multiphase feeding with use of synthetic AAs.

• Other effects of the measure on GHGs

Reducing protein intakes could affect the fertilising value of the manure produced since it generates a reduction in total nitrogen in the manure, as well as the ammonium nitrogen proportion, which is the fraction most rapidly available to plants. In fact, the measured availability of nitrogen for plants remains high, even with a reduced protein content in the diet, suggesting that this change in feed for pigs has little impact on the fertilising value of the manure.

III- Calculations of the abatement potential and cost of the measures

• Systems and calculation methods used

The calculations are made differentiating between animal categories on the basis of the feed rations they receive, then the way their manure is managed (solid manure or slurry).

For **cows**, these categories are based on the standard feed rations described by the Observatoire de l'alimentation des vaches laitières (Dairy cow diet observatory) of the Institut de l'élevage (Institute of Animal Husbandry); an annual calendar of feed rations is used to determine the winter feed rations and their average CP content (using the Mélodie model), along with associated consumption, production and excretion.

For **pigs** a distinction is made between 6 animal categories (gestating and suckling sows, pigs in the early and late post-weaning period, in the growing period and in the finishing period); the compositions of the feed rations for each category are obtained by formulation at the lowest cost on the basis of energy and amino acid requirements; the CP contents of the various rations are calculated.

The animal numbers are taken from the 2010 Annual farming statistics (SAA) database.

The calculations were first of all made using the CITEPA method for 2010 emissions, which applies the 1996 IPCC emission factors. They were performed assuming that the excretion calculations will be adjusted in the future to be sensitive to the feeding practices proposed. The 1996 IPCC calculation method is somewhat dated and not very precise for the calculation of NH_3 emissions. A more precise "expert" method was therefore performed, using the method proposed by the European Environment Agency (*EMEP/EEA emission inventory guidebook 2009*). This method takes into account the effect of feed rations thanks to better modelling of emissions on the basis of the urinary nitrogen fraction and the factors influencing its volatilisation as NH_3.

• Effects of the measure on GHGs and calculation of its unitary abatement potential

Target effect:

• The reduction in N_2O emissions from manure. This results from a decrease in the amount of nitrogen excreted due to the reduction in the amount of nitrogen ingested (pigs and cows) and an increase in urea recycling in the rumen (dairy cows) .

For each type of ration (standard diets per model farm for cows or specific diets per pig category), the amount of nitrogen excreted and the ammonia nitrogen percentage are calculated. The ammonia nitrogen is then assigned to a management method: excretion on grassland (for cattle) or indoors, then slurry or solid manure. Direct N_2O emissions or indirect ones via NH_3 are calculated on the basis of the nitrogen flows excreted with emission factors at each step specific to the two methods used (CITEPA and EMEP).

For cows, the "CITEPA" method globally over-estimates NH_3 and N_2O emissions and calculates emissions that are higher on grazing than indoors, which appears to contradict current data. The average abatement is thus 0.44 kgNH_3/dairy cow/year with the "CITEPA" method, compared to 6.24 kgNH_3/dairy cow/year for the EMEP method.

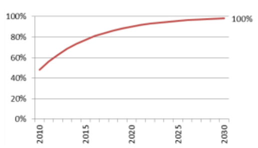
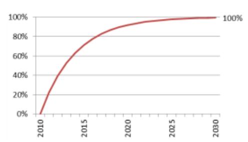
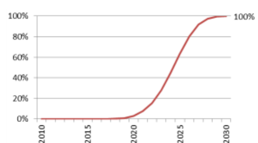
Other effects quantified:

• The reduction in N_2O emissions on manure spreading. While the CITEPA method does not take into account the different manure spreading methods, the EMEP method does so, using different emission coefficients depending on the technology used and the manure composition.

• The modification in induced CO_2 emissions related to substitution of agricultural raw materials in the modified feed rations. This effect upstream of the farm is calculated, for each ingredient in the feed ration, referring to the LCA data available in the Dia'terre® - Ges'tim database (cereals, oilcakes and bran) or otherwise the INRA data (soybean oil, extruded soybean seeds, synthetic amino acids). It should be noted that the calculations can vary quite significantly depending on the sources.

Effects ignored:

•CH_4 emissions, which could rise due to an increase in:
- **enteric fermentation**, modified by the sugar/protein ratio. This effect cannot be taken into account due to a lack of convergence with respect to scientific results at present;
- **manure fermentation**, which could be promoted by the decrease in NH_3 levels (modification of pH) and an increase in the organic

	Sub-measure / Option	A. Dairy cows	B. Pigs – Option 2PAA+	B. Pigs – Option MPAA+
Technical content	**Initial situation**	Currently: a high level of variability in the composition of winter feed rations, with 10 to 18% crude protein (CP)	Two types of feeding: monophase (MP) and biphase (2P) Hypotheses: the protein levels issued by CORPEN are respected; the proteins largely come from soybean meal	
	Change in feed ration	Reduction in the crude protein content of feed rations containing too much protein supplement (target 14%). Calculations for 15 standard feed rations	All year. Use of synthetic amino acids (AAs) in place of oilcakes (soybean and oilseed rape) and peas. Quest for composition by formulation at the lowest cost. Calculations for 6 animal categories	
			Generalise the use of biphase feeding and the use of AAs	Develop multiphase feeding with the use of AAs
Unitary abatement potential	**in N_2O emissions*** (related to manure before and during spreading)	↘ in emissions from manure indoors, during storage, on grassland - "CITEPA" method: not very sensitive to protein feed supplementation practices and good manure management (dairy cows) and not very sensitive to increases in protein consumption (pigs). - "**Expert**" method: modification in protein consumption and different management methods taken into account by the EMEP method.		
		↘ in emissions from manure on spreading - "CITEPA" method: different manure spreading methods not taken into account - **"Expert"** method: the EMEP method uses different emission coefficients depending on the technology used and the manure composition to take into account manure spreading. Hypothesis: no modification in mineral nitrogen fertiliser applications		
	Direct + indirect total* $kgCO_2e$/animal/year	70 / **124**	276 / **510**	381 / **692**
	Induced CO_2 emissions (upstream)	↘ in emissions due to ↘ in nitrogen ingredients in the feed rations ▲ Sensitivity to the LCA data source used (Dia'terre® - Ges'tim database or INRA data)		
	$kgCO_2e$/animal/year	171	306	374
	Total* $kgCO_2e$/animal/year	241 / **295**	582 / **816**	755 / **1066**
Unitary cost	**Cost of feed rations**	Cost of modifying the feed rations, calculated on the basis of 2010 raw material prices		
	Equipment	0	0	Equipment for mixing and distribution (amortised over 12 years) : €29.5/sow/year
	Production losses	During the winter period: reduced production depending on standard feed rations (0 to 25 litres x €0.3/l) + reduction in protein content of milk (-0.1 to -0.3 g/l x €0.006/g/l)	No modification in animal performance	
	Total cost* €/animal/year	**-11.6** (8 to -84)	**-49.2**	**-51.6**
Potential applicability	**Theoretical pot. applicability**	All dairy cows (3,743,390, in 2010)	Pig population: 13,860,000 including 1,119,000 breeding sows	
	Technical criteria	Dairy cows with winter feed rations containing more than 14% CP (detected by the high urea content of their milk > 210-200 mg/l)	Exclusion of boars and unproductive sows In the calculations, piglets and fattening pigs are assigned to sows	
	Max. Technical Pot. Applicability (MTPA)	52% of dairy cows: 1,957,554 cows	951,450 sows with the piglets and fattening pigs they produce per year (28.2 weaned piglets/year/sow)	
Adoption scenario	**2010 reference situation**	48% of dairy cows have winter feed rations with CP ≤ 14%	Feeding: 20% monophase, 80% biphase, 0% multiphase Manure: predominantly managed in the form of slurry.	
	Adoption scenario	Hypothesis: a favourable economic context + high level of farmer awareness 100% of the MTPA reached by 2030 	Hypothesis: a favourable economic context (high oilcake price). Slower kinetics for multiphase requiring an investment 100% of the MTPA for biphase and AA+ by 2030 	100% of the MTPA for multiphase and AA+ by 2030 

* "CITEPA" calculation / **"expert" calculation**

Table 1

matter content of manure (lower digestibility). These effects are ignored since the effect of NH_3 remains poorly documented and the impact on digestibility is limited by the choice of a small reduction in the protein content of rations.

• Estimation of the unitary cost for the farmer

The main cost - negative - is related to the **modification of the composition of feed rations**, i.e. the feed substitutions, with, in particular, a reduction in protein-rich feeds (oilcakes) and the purchase of synthetic amino acids for pigs.

Other costs: only a switch to multiphase feeding for pigs requires the acquisition of specific equipment; only milk production (quantity and protein content) could be affected by modification of feed rations.

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

For dairy cows, the analysis of current standard feed ratios and milk monitoring data concerning urea contents in milk converge to indicate that half of all cows (52%) receive feed rations containing over 14% CPs.
Almost the entire pig herd is concerned by the switch to multiphase feeding, and 20% by the generalisation of biphase feeding.

Measure adoption scenario

Since adoption of the measure does not present any technical obstacles and offers an economic benefit to farmers, the hypothesis adopted is that all animals are fed using the rations proposed by 2030. The adoption kinetics are slower for multiphase feeding due to the need to purchase the required equipment.

IV- Results and their context

		units (M: million)	**Year 2030**				**Cumulative value over the period 2010-2030**		
			Dairy cows	Pigs		**Total Dairy cows + 2PAA+**	Dairy cows	Pigs	
				OT 2PAA+	OT MPAA+			OT 2PAA+	OT MPAA+
Abatement potential ("CITEPA" method) Without induced emissions		*$MtCO_2e$*	0.13	0.26	0.36	**0.39**	1.8	4.0	2.0
Abatement potential ("expert" method)	Without induced emissions	*$MtCO_2e$*	0.23 (0.12 to 0.47)	0.48 (0.24 to 0.96)	0.66	**0.72 (0.36 to 1.43)**	3.2	7.4	3.7
	With induced emissions	*$MtCO_2e$*	0.56 (0.44 to 0.79)	0.77 (0.53 to 1.25)	1.01	**1.33 (0.97 to 2.04)**	7.7	11.9	5.7
Total cost for farmers		*€M*	-21.9	-46.8	-49.1	**-69**	-304.8	-713.9	-277.4
Cost per metric ton of CO_2e for the farmer ("expert" method, without induced emissions)		*€/tCO_2e*	-94	-97	-75	**-96**	-	-	-

Table 2

• The results

This measure has a moderate impact on GHG emissions (0.72 Mt in 2030 adding together the dairy cows and 2PAA+ pigs sub-measures) but offers the advantage of being economically favourable to farmers, even if the savings remain low, at around €20 per cow and per year and €50 per sow per year. The costs per metric ton of CO_2e saved are very similar for the two sub-measures - about -€90/t CO_2e for emissions calculated using the EMEP method -, which seems to be consistent since the two measures link the reduction in the cost of excessive protein use to its urinary excretion, a source of N_2O emissions.

The measure has a greater effect on the consumption of soybean meal per metric ton of concentrated feed for dairy cows than it does for pigs (approximately -11% compared to -8.5%), explaining why the induced emissions abatements are proportionally higher for cows whereas the direct and indirect emissions are slightly lower.

The "dairy cows" sub-measure has a more limited effect on GHG emissions (around half) than the "pigs" sub-measure, but this is largely due to the fact that: not all cows are concerned; of those that are, not all are concerned to the same extent; only the winter ration, which is easy to control, is revised. For pigs, it is the year-round diet that is modified.

The cumulative abatement potential from 2010-2030 is better for the 2PAA+ option, whereas the unitary abatement is higher for MPAA+: this effect results from differences in the adoption kinetics, the adoption of 2PAA+ being much faster.

The calculations for emissions on the farm and upstream demonstrate that the incorporation of industrial amino acids in lower protein diets simultaneously reduces direct N_2O emissions and GHG emissions associated with the production of raw materials for pig feed.

• The sensitivity of the results to the hypotheses

Estimation of induced emissions related to the use of agricultural raw materials is highly sensitive to the calculation method, which currently substantially penalises Brazilian soybean (to which 70% of the conversion of forest into arable land is imputed, with estimated emissions of 740 tCO_2e/ha). It is possible that this method may evolve to more broadly spread the impact of deforestation, which would modify the GHG values of the feeds and could significantly reduce the positive effect obtained on the induced emissions.

For pigs, the performance levels of the animals (sow productivity, feed conversion ratios) have a strong impact on emissions but a low impact on emission differentials (abatement potential) since the impact is comparable for the reference situation and the two technical options.

The scenario of constant animal populations and prices used for the calculations is obviously highly debatable for the quantification of this measure.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effect

The EMEP/EEA method is already used by the CITEPA to calculate NH_3 emissions in the context of another inventory. It would be sufficient to have its use validated for quantification of gaseous nitrogen emissions for the calculation of GHGs.

As regards multiphase feeding, the CITEPA method would make it possible to take it into account in absolute terms. But the CORPEN reference data, used by the CITEPA to perform the calculations, do not reflect its effect.

Verifiability of implementation

The main difficulty for incorporation in the national inventory - irrespective of the method - relates to the availability of reliable data concerning feeding practices, particularly for ruminants. In the case of dairy cows, the urea contents of milk could represent an indicator of nitrogen supplementation practices when the animals are housed indoors, on condition that interpretation of these contents be better validated. For pig feeding, the technical data are more reliable and ought to make it possible to take this effect into account more rapidly.

• The contexts and measures liable to promote the roll-out of the measure

For cows. An increase in the price of protein-containing raw materials (soybean meal) may promote the development of the measure, which is hampered by a common strategy among farmers, consisting in adopting a safety margin for the nitrogen content of feed rations to avoid any risk of limiting production.

For pigs. The adoption of biphase feeding was rapid, because it was promoted by agricultural advisers and its adoption allowed farmers to reduce quantities of organic nitrogen in the context of the "Nitrates" directive (limited to 170 kg/ha). The same ought to be true for multiphase feeding, given the benefits to farmers. An increase in the price differential between protein feeds and energy feeds may make this technique more attractive. However, its adoption will require access to more competitive and numerous synthetic amino acids (for example valine) as well as the capacity to integrate these types of feed into CORPEN standards. It will also require the implementation of investment support and closer monitoring of animal performances.

• Other effects of the measure

- Reducing NH_3 emissions offers a number of benefits, since this substance is also involved in acidification, eutrophication (via re-depositing and conversion into nitrate) and soil toxicity processes, and has an impact on human health (fine particles).

- By reducing soybean meal imports and promoting the use of resources produced in France, the measure increases the protein independence of the country. For pigs, it contributes to the competitiveness of farms thanks to a beneficial reduction in feed costs.

- A change in raw material consumption by livestock could modify arable areas on a national scale, but this effect is uncertain, since the modification may concern imported products.

• Conclusions

This measure is one of the "win-win" measures, the implementation of which may appear to be easy. However, it is necessary to acknowledge that obstacles exist, at least for dairy cows; otherwise they would almost all already be receiving the recommended diet. An increase in the price of dietary proteins would clearly promote the development of this measure.

Using the figures taken from the EMEP method, the cumulative effects of the two sub-measures are over 11 million metric tons of CO_2e over the period 2010-2030, to which can be added 8.9 million metric tons of CO_2e induced upstream by the feed sources used, even if these effects may not concern French inventories.

The abatement potential remains globally limited in terms of impacts on GHG but the incorporation of a more precise method in the calculation of inventories would be sufficient to increase the scope.

9 Develop methanisation and install flares to reduce CH_4 emissions related to livestock manure storage

↘ CH_4

A. Develop methanisation
B. Cover storage pits and install flares

I- Challenge and principle of the measure

At present, most of the livestock manure collected (approximately 150 million metric tons per year) is stored in farm buildings and in outdoor structures or in fields for a period of up to 6 months. This storage is accompanied by direct emissions into the atmosphere of gas compounds and, in particular, CH_4 and N_2O, which accounted for 13.7 and 5.2 million metric tons of CO_2 equivalent ($MtCO_2e$), respectively, in 2010, i.e. 13% and 4.9% of all emissions from the French agricultural sector.

The objective of the measure is to develop capture of the CH_4 produced during this storage phase and then eliminate it via combustion. The CH_4 is burned - and hence converted into CO_2 - either in boilers or cogeneration units - used to produce electricity and/or heat - or simply by flaring. Since the global warming potential (GWP) of CO_2 is 25 times lower than that of CH_4, the combustion of CH_4 into CO_2 leads to a significant reduction in the greenhouse effect, even in the absence of any conversion to energy (case of flares).

Since the very great majority of CH_4 emissions related to manure management are produced by the cattle (60%) and pig (25%) sectors, the measure only takes into account these two species.

II- Mechanisms and technical methods of the measure

• Livestock manure emissions

These emissions depend primarily on the aerobic and/or anaerobic conditions in which the manures are stored: these conditions determine the type of degradation the organic matter undergoes and hence the associated gas emissions. This key factor leads to a major distinction between slurry and solid manure, respectively presenting totally or partially anaerobic conditions.

CH_4 emissions

These emissions during manure storage are quantitatively high but very variable. They depend on a number of factors, including the animal species, the type and composition of the manure, the storage conditions (temperature, etc.) and duration.

CH_4 emissions resulting from the fermentation that occurs in anaerobic conditions will be high for slurry, and in liquid products more generally, and will be low in solid manure and, for all products, following spreading in the field, where conditions are very predominantly aerobic.

In the calculation methods developed by the IPCC, the effect of the animal species is taken into account by estimating, for each animal species, the quantity of organic matter excreted (VS) and a maximum methane producing capacity for this organic matter (B_0). The effect of the manure management method is then taken into account by a "Methane conversion factor" (MCF, in %) enabling calculation of the emission by adjusting the B_0 on the basis of the management methods. Hence, the values (defined for a given climate) differ greatly between solid manures and slurries (Table 1).

	Anaerobic conditions (slurry, digestates)	**Aerobic/anaerobic conditions** (solid manure, grassland)
Methane conversion factor (% CH_4 emitted into the atmosphere)	**45%**	**1.5%**
Volatilisation factor (% N volatilised into N_2O)	**0.1%**	**2%**

Table 1. MCF and VF values (in temperate climates)

During manure storage, the CH_4 production conditions are not optimal (relatively low temperature, microorganisms not adapted, etc.) and the resulting emission kinetics are relatively low and constant for a given climate. Consequently, the main factor determining cumulative CH_4 emissions is the storage duration. Methane emissions were therefore considered to be proportional to storage duration.

N_2O emissions

The production of N_2O requires both aerobic and anaerobic conditions, promoting nitrification and denitrification respectively. N_2O emissions are therefore significant for solid manure and, conversely, very low in liquid effluents (slurry and products resulting from methanisation).

Once again, the effect of the manure management method is taken into account using a "Volatilisation Factor" (% N volatilised into N_2O) - the values for which are indicated in Table 1.

• The sub-measures studied

Methanisation consists in sending manure to an anaerobic digestion reactor at the earliest possible stage, promoting the production of CH_4 and enabling its capture. This CH_4 can be injected into the natural gas network but is generally converted into energy by combustion in boilers or cogeneration units, producing heat and/or electricity. This technique can be applied to all the livestock manures collected, either liquid or solid (slurry and solid manure).

In the majority of cases, co-substrates from the farm (crop residues, etc.) or outside (food industry waste, etc.) are methanised with the manure in order to increase biogas production. Due to the significant diversity in these practices, and the fact that the effects of methanisation are not then necessarily imputable to the agricultural sector alone, the addition of co-substrates was not taken into account in the abatement and cost calculations despite the fact that this contributes to the profitability of the methanisation unit.

The other sub-measure studied is **covering** of the storage pit, making it possible to collect the CH_4 produced, and installation of a **flare** to burn this CH_4. This method, which can only be applied to stored liquid waste, will only be considered for farms in which the amount of slurry produced is insufficient to justify methanisation equipment.

• The effects of "methanisation" and "flaring"

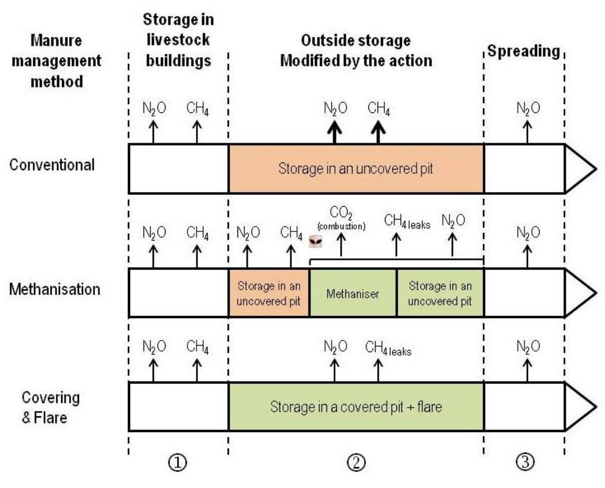
The emissions potentially modified (Figure opposite) are those occurring after the indoor storage phase: during outdoor storage in the open air (reduced upstream of methanisation and eliminated by covering pits); during any downstream storage and spreading.

CH_4 emissions are reduced by upstream storage for a shorter period followed by CH_4 combustion. The emissions of methanised manure are then considered to be low.

By storing manure in strictly anaerobic conditions, the recovery/combustion process also reduces N_2O emissions when replacing aerobic/anaerobic conditions (solid manure) – however, the impact is nil for manure in liquid form, already in anaerobic conditions and emitting little N_2O. The treatment process also modifies the characteristics of the residual product - particularly the biodegradable organic carbon content - and therefore has an impact on the processes involved in N_2O emissions after spreading (particularly denitrification). However, the data available - sparse and sometimes contradictory - do not all these effects to be determined and quantified.

The processes involved in the reduction of CH_4 emissions (anaerobic degradation of organic matter from manure under controlled conditions or otherwise) are well known, and their scientific basis is not disputed. However, quantification of this reduction is open to debate.

In fact, the results depend greatly on the scenarios - with and without the measure - adopted, and the calculation hypotheses applied, something that is difficult to determine accurately due to the significant diversity of situations and the lack of available data.



① Indoor storage, and hence the resulting CH_4 emissions, not modified by the measures proposed.
② Methanisation: reduced upstream storage (generally in open air), low-emitting downstream storage (CH_4 already emitted and/or covered storage).
② Covering & flare: no upstream or downstream open-air storage.
③ Spreading conditions (predominantly aerobic) little modified.

• Other effects of the measure on GHGs

When the CH_4 captured is converted into heat and/or electricity, the energy produced may replace a CO_2 emitting energy (usually fossil fuel for heat and French electric mix for electricity).

Finally, methanisation could have an impact on synthetic nitrogen fertiliser consumption if the digestate presents a fertilising value greater than that of untreated manure. However, the data available do not enable the potential effects - highly dependent on the context - to be determined and quantified.

III- Calculations of the abatement potential and cost of the measures

• Systems and calculation methods used

Given the high level of system diversity associated with the type of animals, the manure management method (solid manure or slurry) and its conditions (accumulated litter, daily raking of liquid or solid manure or animals on slatted floors, etc.) and the absence of existing data concerning the conditions for the various manure management methods, it was decided to use a reference for each of the animal categories considered (cattle and pigs) in order to determine the temporal distribution of manure storage between indoors and outdoors. Each of these cases is defined selecting the animal category emitting the most GHGs and coupling it with the most widely used system.

The situations used as references are:
- for cattle: dairy cows on slurry, with daily raking of manure towards an external pit, where it is stored until spreading;
- for pigs: fattening pigs housed on slatted floors (slurry system) where manure is considered to be stored indoors 20% of the time and outdoors 80% of the time before spreading.

The temporal data relative to manure storage between indoors and outdoors pits (spreading every 6 months) are then applied by extrapolation to all animals in the category considered.

The data concerning the animal numbers are taken from the 2010 Annual farming statistics (SAA) database; those concerning the herd sizes of farms (used only to determine the maximum theoretical potential applicability) come from the RICA database. The frequencies of manure management method systems (slurry, solid manure or grassland) are derived from data from "Livestock buildings" surveys.

• Estimation of unitary abatement potential

Target effect:

. The reduction in CH_4 emissions resulting from its capture and combustion. This is limited by the existence of open-air manure storage upstream and downstream of the process, and by CH_4 leaks from installations.

The CITEPA calculation method for 2010 emissions adds together all the emissions without distinguishing between indoor and outdoor storage and does not incorporate the methanisation or

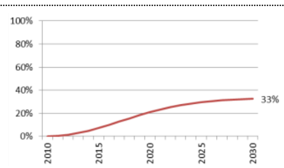
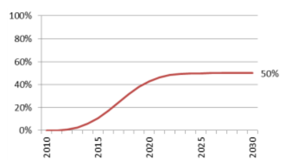
	Sub-measures	A. Methanisation	B. Covering & flare
Technical content	**Initial situation**	Cattle with manure storage entirely outdoors (with spreading every 6 months). Pigs: manure stored indoors 20% of the time and outdoors 80% of the time (with spreading every 6 months).	
Technical content	**Change in manure management**	Upstream outdoor storage limited to 3 weeks (duration reduced by 88%) Digestion in a reactor with energy production	Upstream outdoor storage duration identical to the reference situation, but with covering, capture and combustion of CH_4 No conversion to energy
Unitary abatement potential	**CH_4 emissions**(manure fermentation)	Emissions proportional to the storage duration + leaks Cows: MCF = 6.9% of the B_0 (upstream storage: 0.12x45% + leaks: 1.5%) Pigs: MCF = 5.8% of the B_0 (upstream storage: 0.12x36% + leaks: 1.5%)	No upstream or downstream storage Leaks (MCF = 1.5% of the B_0)
Unitary abatement potential	**N_2O emissions** (during manure storage)	For solid manure only, reduction in emissions due to switch to anaerobic conditions: 630 $kgCO_2e$/animal/year for dairy cows, for example	-
Unitary abatement potential	**Direct + indirect total** $kgCO_2e$/animal/year	Dairy cows & solid manure: 430 Dairy cows & slurry: 1,440 Fattening pigs > 50 kg & slurry: 340	Dairy cow & slurry: 1,640 Fattening pigs > 50 kg & slurry: 400
Unitary abatement potential	**Energy substitution**	Electricity: 50 $kgCO_2e$/animal/year; Heat: 70 $kgCO_2e$/animal/year for dairy cows, for example	0
Unitary abatement potential	**Total** $kgCO_2e$/animal/ year	Dairy cows & solid manure: 550 Dairy cows & slurry: 1,560 Fattening pigs > 50 kg & slurry: 370	Dairy cow & slurry: 1,640 Fattening pigs > 50 kg & slurry: 400
Unitary cost for the farmer	**Investments**	Investment of €9000/kWe amortised over 16 years	Covering a surface area of 215 m² (€280/m²) Purchase of a flare: €21,000 (amortised over 16 years)
Unitary cost for the farmer	**Operating costs**	Maintenance by outside service company (including €18/MWh for the cogeneration unit and 1.3% of miscellaneous investment), insurance (0.4% of investment), electricity consumption (7% of electricity production at €71/MWh) Labour: maintenance carried out by farmer (€14/MWh) and monitoring	Labour: maintenance and monitoring (€1000/year)
Unitary cost for the farmer	**Revenues**	Sale of electricity corresponding to 25.6% of the "methane" energy potential at €130/MWh ▲ *Use of heat not taken into account*	0
Unitary cost for the farmer	**Total**	€8,283/farm/year for a 50kWe unit	€10,075/farm/year
Potential applicability	**Theoretical potential applicability**	All cattle and pigs	
Potential applicability	**Technical criteria**	The minimum power of cogeneration plants existing on the market (15 $kW_{electric}$) corresponding to a farm with at least 140 LSU approximately.	Only applies to liquid manure ▲ sub-measure retained only for livestock numbers not concerned by methanisation.
Potential applicability	**Max. Technical Pot. Applicability (MTPA)**	Livestock on farms with > 140 LSU (i.e. 62% of total livestock numbers, corresponding to approximately 48,800 farms).	40,000 farms
Adoption scenario	**2010 reference situation**	In 2011: 48 agricultural methanisation units or based predominantly on livestock manure (< 1 Mt, i.e. < 1% of recoverable manure)	No installations currently in France
Adoption scenario	**Adoption scenario**	Favourable context (support, energy purchase prices), but development limited by the capacities of the construction and equipment sector: installation of 680 units/year → The MTPA is achieved in 2084; in 2030, 12,200 farms, representing 33% of total cattle and pig numbers, are equipped, i.e. 53% of the MTPA in terms of livestock numbers and 25% in terms of farm numbers 	Installation of 1000 units/year → Situation in 2030: 50% of the MTPA, i.e. 20,000 farms 

Table 2

covering/flare manure management method: it cannot therefore take into account the effects of the measure. The "expert" calculation method, divides emissions up into several phases (upstream storage, process, downstream storage) then allocates a specific factor for conversion of organic matter into methane (MCF) for each of these phases; these factors per phase are finally added together to determine a global MCF for each manure management option considered.
Since emissions are considered to be proportional to the duration, reducing upstream outdoor storage from 6 months to 3 weeks leads to an approximately 88% reduction in emissions. Emissions or their changes occurring during downstream storage (low because hypothesis of high level of conversion into CH_4) and following spreading are ignored.
Biogas leaks due to the defective seal of installations (at pit cover, reactor and combustion system level) are estimated to be 1.5% of the CH_4 produced.

The CO_2 resulting from this combustion of CH_4 is not counted since it is a short-cycle carbon.

Other effects quantified:

. The reduction in N_2O emissions resulting from the switch to completely anaerobic storage conditions. For slurries, the emissions are identical with or without the measure. However, for solid manures, the N_2O emissions are reduced, with the global VF falling from 2 to 0.1% for cattle and from 2 to 0.48% for pigs, assuming emissions identical to a solid manure for the upstream methanisation part and emissions identical to a slurry for the downstream methanisation part.

. The reduction in CO_2 emissions resulting from the substitution of fossil energy (effect induced upstream of the farm). The energy produced by methanisation is calculated by considering that 80% of the remaining MCF at the entrance to the biogas plant is recovered as CH_4, and that 32% of this CH_4 is then converted into electricity (substitution of 78 gCO_2 per kWh produced) and 15% into heat (substitution of 245 gCO_2/kWh).

Effects ignored:

- **volatilisation of NH_3** during downstream storage and spreading, which could be increased by the product treatment process. However, appropriate techniques (covering of pits for storage and drop hoses for spreading) exist and enable a low impact to be obtained;
- **nitrification/denitrification on spreading** i.e. N_2O emissions on spreading: the data in the literature are conflicting and the effect is therefore ignored;
- **the fertiliser saving** due to a greater fertilising capacity of methanisation digestates (effect uncertain as knowledge currently stands).

• Estimation of the unitary cost for the farmer

These **costs** include the initial investment (amortised over 16 years) and the costs of operating the installations (maintenance by a service-provider, etc.) to which are added the monitoring and maintenance labour performed by the farmer. For "methanisation", the simulation is performed for an average-sized farm requiring a methanisation unit of 50-70 $kW_{electric}$. For "covering & flare", the calculation considers a farm with 100 LSU and an annual production of around 1500 m^3 of slurry: the investment includes covering 215 m^2 of pit and the purchase of a flare, to which maintenance costs are to be added.

For **methanisation** only, additional **revenues** are generated by the sale of electricity to the grid – the technical and economic uncertainties prevented a financial value for heat being taken into account.

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

All cattle and pigs for which some or all of the manure is collected are theoretically concerned ("theoretical potential applicability").
For "methanisation", the potential applicability is restricted by the minimum power of the cogeneration plants available on the market (15 $kW_{electric}$, i.e. a minimum annual electric energy of approximately 120,000 kWhe), which requires the manure of at least 140 LSU approximately to operate. It should be noted that the availability of co-substrates with a high methane-producing potential - upon which the profitability of installations depends in current economic conditions - is not taken into account.
The "covering & flare" option does not present any major technical limitations but it only applies to liquid manures, as well as to farms on which the herd is insufficient to make methanisation equipment viable.

Measure adoption scenario

In the current favourable context (support, energy purchase prices), the development of **methanisation** is limited by the capacities of the construction and equipment sector. In Germany, where the prices are interesting, the rate of installation has been around 680 units/year over the past few years. Consequently, this adoption scenario has been selected. The French plan, published in March 2013, sets a target of 1000 biogas plants by 2020, i.e. 130 installations per year, on average, but this plan considers units with an average power of around 200 kWe, which corresponds for each unit to 3-4 farms considered in this study, hence an installed power of the same magnitude.

For "**covering/flare**", based on the development of equipment of the same type, the hypothesis adopted is the equipping of 1,000 farms per year.

IV- Results and their context

• The results

Methanisation measure

The unitary abatement potential depends on the animal category considered, as well as the manure management system. Hence, for example, the direct emissions abatement potential ranges from 0.34 to 1.44 tCO_2e/animal/year for fattening pigs and dairy cows, respectively.

The application of a (calculation) method adapted to 33% of the MTPA leads to an annual abatement of 5.78 $MtCO_2e$ direct GHG emissions. By applying the adoption kinetics, the cumulative figure over the period 2010-2030 is 62.9 $MtCO_2e$ for direct emissions.

The cost associated with this measure is estimated to be €17/metric ton of direct CO_2e avoided, with an annual cost in 2030 of €99.9 M and a cumulative cost over the period 2010-2030 of €1,087 M.

		units (M: million)	Year 2030			Cumulative value over the period 2010-2030	
			Methanisation	Flares	**Total 2 sub-measures**	Methanisation	Flares
Abatement potential ("CITEPA" method) Without induced emissions		$MtCO_2e$	0	0	**0**	0	0
Abatement potential ("expert" method)	Without induced emissions		5.8 (3.8 to 6.9)	3.4 (2.0 to 4.7)	**9.2 (5.8 to 11.6)**	62.9 (40.9 to 74.8)	45.4 (26.7 to 62.7)
	With induced emissions		6.3 (4.1 to 7.5)	3.4 (2.0 to 4.7)	**9.7 (6.3 to 12.1)**	68.7 (44.7 to 81.7)	45.4 (26.7 to 62.7)
Total cost for farmers		€M	100	201.5	**301**	1086.6	2697.2
Cost per metric ton of CO_2e for the farmer ("expert" method, without induced emissions)		€/tCO_2e	17	59	**35**	-	-

Table 3

Flare measure

As with methanisation, the unitary abatement potential depends on the animal category. This potential ranges, for example, from 0.4 to 1.64 tCO_2e/animal/year for fattening pigs and dairy cows, respectively.

The application of a (calculation) method adapted to 50% of the MTPA leads to an annual abatement of 3.4 $MtCO_2e$ of direct GHG emissions. By applying the adoption kinetics, the cumulative figure over the period 2010-2030 is 45.4 $MtCO_2e$ for direct emissions.

The cost associated with this measure is estimated to be €59/metric ton of direct CO_2e avoided, with an annual cost in 2030 of €201.5 M and a cumulative cost over the period 2010-2030 of €2,697 M.

Since the "covering & flare" sub-measure is only envisaged for farms not concerned by the "methanisation" solution, the two sub-measures are additive.

• The sensitivity of the results to the hypotheses

Calculation of the abatement potential is sensitive to the hypothesis adopted for distribution of manure emissions between indoor and outdoor storage. Assuming a hypothesis - more unfavourable, but realistic - whereby 20% of storage is indoors for cattle (0% in the average scenario) and 40% for pigs (20% in the average scenario), the abatement falls to 3.98 $MtCO_2e$ for "methanisation" (i.e. a 30% reduction compared to that calculated in the average scenario), and to 2.35 $MtCO_2e$ for "covering & flare".

The abatement is also sensitive to the values adopted for emissions without the measure. Recent studies and the 2006 IPCC guidelines revise the quantities of organic matter excreted and the MCFs for conventional management - particularly of slurry - downwards. These revisions lead to CH_4 emission calculations without any measure being reduced by 3 to 3.5 $MtCO_2e$ (i.e. -20 to -25%), generating a reduction in abatement potential of the same magnitude (20-25%), i.e. direct emissions abatements of approximately 3.8 and 2.2 Mt for "methanisation" and "covering & flare", respectively.

For "methanisation", the application of development scenarios that are more (1000 units/year) or less (540 units/year) favourable leads to direct emissions abatements of 6.9 and 5,3 Mt, respectively.

The calculation of costs varies significantly depending on the price hypotheses used: for methanisation, the cost per metric ton of CO_2e is thus €6.6 and €27.9 for investment costs of €7,500 and 10,500/kWe (price range taken from technical documents) and can be as high as €35.5 when higher operating costs are considered (€735/kWe installed); it falls to -€2.5/tCO_2e (profit) with the electricity purchase price in force since 2011 (€170/MWh). For a subsidy-free electricity purchase price (€54/MWh), this cost is estimated to be €54.9.

As regards "covering & flare", there is a high level of uncertainty with respect to the number of farms concerned in order to achieve the targets set, as well as the pit surface areas to be covered. These data have an impact on the associated costs via the number of flares required and the covering surface areas necessary. Study of the sensitivity of these variation factors revised upwards (50%) brings the unitary cost to €89/tCO_2e.

• The conditions for incorporation of the measure in the national inventory

Quantification of the effect

Application of the "CITEPA" calculation method does not allow this measure to be taken into account, and the abatement in the inventory is therefore zero. The two sub-measures could nonetheless be taken into account relatively easily by considering them to be manure management systems with specific MCFs (as proposed by the 2006 IPCC guidelines).

Verifiability of implementation

For "methanisation", the CH_4 produced is converted into energy, usually in the form of electricity, generating a contract with EDF and regular measurement and control of this production. The use of these data and the application of an average ratio of tCO_2 avoided/kWh of energy produced could make it possible to verify the implementation of this measure. However, the energy produced may come from other substrates and it therefore appears to be necessary to schedule the traceability of inputs in quantitative and qualitative terms.

For "flares", given that there is no energy conversion implemented, the verifiability of the measure proves to be more difficult. However, this could be envisaged by placing biogas meters before the flare.

• The contexts and measures liable to promote the roll-out of the measure

For "**methanisation**", the difficulties and time involved in the administrative examination of applications represent a limit to the development of the measure, extensively underlined in the various reports. Furthermore, the management of digestates - where this needs to be significantly modified compared to the situation before implementation of the measure - is also an obstacle to the development of this measure given the digestate certification/ standardisation difficulties. Finally, the average cost calculated with the current electricity purchase price is close to €0 but, in reality, this masks significant variations depending on farm type and size and thus appears to be insufficient for maximum development of the measure.

Methanisation benefits from political support, reflected by a variety of aids, variable in time and space, from agencies (in particular the ADEME) and local authorities. For example, a "Methanisation" plan was submitted to the Ministry of Agriculture at the end of March 2013 and targets the development of 1,000 biogas plants by 2020, which is similar to the development envisaged in this study, as indicated above.
In the current context, the development of methanisation is increasing, even without additional measures, thanks to the support offered. The dynamics are likely to gather pace due to reassessment of the purchase price for electricity produced by biogas in May 2011, and of the natural gas network injection prices and dual use (electricity/injection) conditions published more recently.

For "**covering & flare**", the technical feasibility on a national scale remains to be demonstrated (research project underway) and the funding of this type of measure via the carbon market does not currently appear to be secured.

• Other effects of the measure

The increased volatility of ammonia (NH_3) as a result of methanisation may lead to an increase in emissions of the gas into the atmosphere downstream of the process (storage and spreading) if appropriate measures are not taken. The measures considered have no direct impact on the nitrogen contents of manures. Consequently, these measures have no direct impact on potential nitrogen transfers to the aquatic environment. However, for "methanisation", the supply of substrates from outside the farm, not incorporated in the calculations but existing in reality, may lead to an increase in nitrogen pressure on the farm. The supply of substrates other than livestock manure may also lead, for substrates not emitting CH_4 in the current management option, to an increase in CH_4 emissions linked to these substrates via leaks in biogas plants.

In addition, the "methanisation" measure contributes to the policies implemented regarding renewable energies.
Finally, the combustion of the gas produced containing traces of nitrogen substances may lead to an increase in nitrous oxide (NOx) emissions, particularly for the "covering & flare" measure in which the combustion and emissions are not very well controlled.

• Conclusions

Two sub-measures were studied within the framework of this measure, with annual abatement potentials of 5.78 and 3.4 $MtCO_2e$ achieved in 2030 for methanisation and covering/flare respectively and a cumulative total of 9.18 $MtCO_2e$/year. However, the costs associated with methanisation are three times lower since, although the investments and operating costs are much higher, the subsidised sale of electricity partially offsets these costs. In addition, this methanisation sub-measure leads to the production of renewable energy. For the 2 sub-measures, the cost calculations were performed using macroscopic data on the basis of an average farm and therefore correspond to average costs. Economies of scale will lead to lower costs for the biggest farms and higher costs for the smallest ones. The various areas of uncertainty and sensitivity studies reveal that the uncertainty for the abatement potentials is approximately 20-25% and may even be higher (50%) if all the uncertainties are considered to be unfavourable. In terms of costs, the sensitivity studies demonstrate that, depending on the hypotheses, the unitary cost of methanisation ranges from -€2.5 to €54.9/tCO_2e whereas the cost for covering/flare can be as high as €90/tCO_2e.

Ultimately, although numerous uncertainties emerge, with respect to both the abatement potential and the associated costs, these measures generate a promising level of abatement. Furthermore, methanisation is a measure that is already developing, particularly due to its interest in terms of renewable energy production. However, the implementation of these measures - particularly methanisation - needs to be supported and the negative effects induced - such as NH_3 emissions and CH_4 leaks - need to be controlled.

10 Reduce the fossil fuel consumption of agricultural buildings and machinery on the farm to limit direct CO_2 emissions

↘ CO_2

A. Reduce fossil fuel consumption for heating livestock buildings
A. Reduce fossil fuel consumption for heating greenhouses
C. Reduce the fossil fuel consumption of agricultural machinery

I- Challenge and principle of the measure

With 3650 ktep consumed in 2012, the agricultural sector accounts for 2.4% of national energy consumption in France, purely taking into consideration the energy consumed directly on the farm. The first consumption component corresponds to agricultural machinery and the second to buildings (greenhouses, livestock housing, dryers, milking parlours) for heating, ventilation, lighting, etc.

The main energy sources used are fossil fuels (natural gas, diesel, fuel oil) and electricity. The associated GHG emissions occur mainly on the farm for fossil energies (*direct* emissions from farm machinery, for example), and upstream of the farm for electricity (*induced* emissions, related to the production of electricity in thermal power plants, for example). Emissions due to the direct consumption of fossil energy were estimated to be 11 million metric tons of CO_2 equivalent ($MtCO_2e$) in 2010 for farming, forestry and fishing, which are combined in the national inventory, i.e. 10% of French agricultural sector emissions.

The measure aims to implement technical solutions in order to reduce fossil fuel consumption and the associated direct emissions on the farm. A reduction in induced emissions is not targeted. Activities and units using electricity are not targeted by the measure, therefore, since the associated emissions are produced outside the farm. Replacing fossil energy with renewable energies produced on the farm does not fall within the scope of the measure either.

The aim - with this measure, as with the study as a whole - is not to be exhaustive but to examine a few cases presenting a significant potential for GHG emissions abatement. The three sub-measures retained are a reduction in the energy consumption of buildings used to house meat poultry (heated with natural gas), greenhouses and tractors.

II- Mechanisms and technical methods of the measure

• Emissions linked to the use of fossil energy

The consumption of fossil energies (products derived from oil, natural gas, etc.) primarily generates CO_2 emissions, but it can also emit nitrogen oxides - including nitrous oxide (N_2O) - if combustion is incomplete. For this reason, the emission factors assigned to the different fossil sources (Table 1) are expressed in CO_2 equivalent (CO_2e).

These emission factors make a distinction between *direct* emissions, linked to combustion on the farm, and the associated *induced* emissions, occurring upstream during the production and transfer of fuels; the latter are significantly lower. These factors are not discussed or revised: the values used by the IPCC in 2006 differ very little from those used in 1996.

• Knowledge of energy consumptions

The uncertainties concern the consumptions and energy savings, i.e. the energy consumption of buildings and installations in place, the performance of the various installations (heating or insulation, for example) and the effects of practical conditions of use (optimisation or otherwise of settings, etc.), as well as national statistics relating, for example, to the size of the country's tractor fleet, etc. When assessing the effects of energy saving measures it is therefore necessary to consider the question of technical reference availability and reliability.

Type of fuel	Direct emissions ($kgCO_2e/kWh$)	Induced emissions ($kgCO_2e/kWh$)
Natural gas	0.205	0.04
Propane/butane	0.231	0.57
Domestic heating fuel/ Diesel	0.271	0.03
Heavy fuel oil	0.282	0.04
Coal	0.341	0.07

Table 1. Direct (combustion) and induced (production) GHG emissions factors of fossil fuels (Source: ADEME 2010)

As regards the current energy consumptions of greenhouses and buildings housing livestock, the references supplied by the CPDP[13] (used by the CITEPA) give a natural gas consumption for agricultural activities (greenhouses + livestock buildings) of around 260 ktep for 2005 (230 ktep for 2011). But the calculations made for this study, on the basis of consumptions recorded in 2005-2006 (published by the CTIFL, the IFIP and the ITAVI), generate a figure of 430 ktep (without taking into account frost protection tunnels and the contribution of livestock buildings housing pigs and calves using natural gas).

As regards the performance of the various materials and installations, references are disseminated with the introduction of a number of mechanisms (PPE, CEE, etc.; see section IV) in recent years aimed at increasing energy savings.

Finally, for numerous simple energy-saving techniques (setting adjustments, etc.), no references are available quantifying their effects; they cannot be taken into account therefore.

• The sub-measures and technical options studied

The cases examined were chosen because they significantly contribute to fossil energy consumption on farms on a national scale, and because energy-saving techniques are available on the market for which the effects are documented.

[13] Abbreviations used. CPDP: *Comité professionnel du pétrole* (Professional Oil Committee); CTIFL: *Centre technique interprofessionnel des fruits et légumes* (Inter-trade technical centre for fruit and vegetables); IFIP: *Institut du porc* (Pig Institute); ITAVI: *Institut technique de l'aviculture* (Technical institute for poultry farming).

A. Buildings housing meat poultry. These were chosen because they are heated mainly by propane (unlike buildings housing cattle and pigs, which are more often heated with electricity). The heating saving proposals examined are:

1. the installation of air-to-air heat exchangers (which would enable a proportion of the heat contained in the air extracted from the building to be taken and transferred to the new air entering the building);
2. the installation of recent technical heating equipment: new-generation radiating heating panels or air heaters (indoor hot air cannons suspended in the building);
3. insulation of the building.

B. Heated greenhouses. For these greenhouses dedicated primarily to the production of cucumbers and tomatoes, the two proposals are:

1. the installation of a double thermal screen positioned over the crops to reduce calorie losses;
2. the installation of a hot water storage tank (conventional or open buffer) which (via partial or complete decoupling of heat production and its distribution in the greenhouse) allows the heater to work at a constant rate with a maximum yield.

C. Tractors. These represent around 90% of the total diesel consumption of French farm machinery. The two abatement avenues are:

1. engine diagnosis by passing tractors over an engine test bench (ETB), making it possible to optimise engine adjustment;
2. application of eco-driving rules (promoted, in particular by machinery cooperatives).

• Other effects of the measure on GHGs

By modifying the atmospheric conditions inside livestock buildings, techniques such as heat exchangers and improved insulation may reduce ammonia (NH_3) emissions, and lead to drier bedding that emits less methane (CH_4) and is lighter (diesel savings when removing waste from the building). Because of the lack of information concerning the emissions reduction, these effects will not be quantified.

III- Calculations of the abatement potential and cost of the measures

• Systems and calculation methods used

The abatement potential and cost calculations concern the following systems:

Poultry buildings. Since the technical references available concerning energy use (ITAVI) are expressed per animal produced, this unit will be used for the unitary calculations. The calculations made distinguish between 10 poultry categories defined by the species (chicken, guinea fowl, duck and turkey) and type of production (standard or with a longer rearing period); the animal numbers are taken from the 2010 Annual farming statistics (SAA) database. The equipment is calculated on the basis of an average-sized building (1,200 m^2). The fuel used is propane.

Greenhouses. The analysis distinguishes between market gardening and ornamental horticulture greenhouses (the equipment used is different), as well as the numbers per fuel used (natural gas, propane/butane, domestic heating fuel, heavy fuel oil or coal). The calculations are made per surface area unit; the source for the statistics is the 2010 agricultural census.

Tractors. The calculations, made per tractor, consider two engine categories, depending on their power (a horsepower of under or over 80). The source for the statistics is the "Equipment" census conducted in 2005 (Agreste).

The energy savings resulting from the different technical solutions envisaged are given in Table 2. For some techniques, the energy saving appears to be variable, depending on the type of equipment, but also on climate conditions, for example. In the case of insulation, the performance depends, in particular, on the surface areas treated (roof, basement and/or sides). Only the average values are indicated here.

• Estimation of unitary abatement potential

The only effect taken into account is the reduction in fossil fuel consumption, which reduces direct GHG emissions (primarily CO_2, the target effect) as well as emissions induced upstream of the farm. The direct emissions are counted in the "Energy" category (1A4C) of the national inventory - which aggregates agriculture, forestry and fishing.

To estimate these emissions, the method used by the CITEPA for the 2010 inventory multiplies the annual fossil energy consumptions (by type of fuel) by the emission factor allocated to the fuel used (see Table 1).

The "expert" calculation method takes the principle, calculation methods and emission factors applied by the CITEPA, but, for livestock buildings and greenhouses, uses the energy consumption references determined by the technical institutes concerned (ITAVI and CTIFL) rather than those of the CPDP. The induced emissions are estimated using the emission factors supplied by the Carbone® database.

The energy savings (expressed as a % of initial unitary consumption) resulting from the technical solutions examined are determined:
- for poultry buildings, mainly according to the references of Good environmental practice guidelines (Livestock farming-Environment joint technological network (RMT)). For heat exchangers, in particular, the high variability in the performances stated should be noted (values based on very few studies, equipment in the process of being developed, etc.);
- for greenhouses, according to the indications in energy savings certifications, and technical data from the CTIFL and the agronomic research group (EPHOR);
- for tractors, according to tests and trials on the ground carried out by the AILE association (association for local energy and environment initiatives) and the values defined in the energy saving certificates concerning the engine test bench.

• Estimation of the unitary cost for the farmer

The cost for the farmer includes:
- the investment cost associated with purchasing and installing equipment (amortised over 7 or 15 years, depending on the cases) and, potentially, the shortfall to be made up while construction work is being carried out; the operation thereafter does not lead to any additional costs or modification in labour time;
- the fuel savings permitted by the measure, calculated on the basis of 2010 energy prices.

The balance (amount of investment and expenditure avoided) is

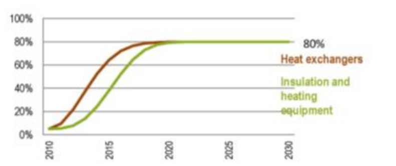
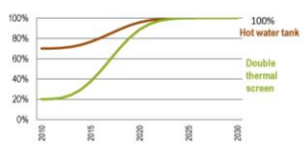
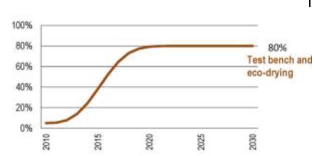
	Sub-measures	A. Poultry buildings			B. Heated greenhouses		C. Tractors.	
		1. Heat exchangers	**2.** Air heaters and radiating heating panels	**3.** Insulation	**1.** Thermal screens	**2.** Hot water tank	**1.** Test bench	**2.** Eco-driving
Technical content	**Initial situation**	Heating with propane 10 animal categories Consumption in kg gas / animal: from 0.033 (chicken for export) to 0.369 (certified turkey)			Heating: natural gas, propane/butane, domestic heating fuel, heavy fuel oil or coal 2 types of greenhouses: market gardening or ornamental horticulture		Diesel consumption: <80 hp: 5 l/h; >80 hp: 10 l/h Use: 500 h/year	
	Modification in equipment	Improve the heating and insulation system (unit = animal produced)			Improve insulation and install hot water tanks (conventional or open buffer) (unit = greenhouse surface area)		Reduce diesel consumption Eco-driving Adjustments after ETB (unit = tractor)	
	Energy savings	15 to 50% depending on the number and type of heat exchangers (Average = 32.5%)	Air heaters: 25%	30 to 50% (Average = 40%)	5 to 22% (Average = 13.5%)	7%	10%	20%
Unitary abatement potential	Range Unit	depending on animal category (chicken for export to certified turkey) kgCO_2e/animal produced			depending on fuel and geographic area kgCO_2e/m²/year		kgCO_2e/tractor/year	
	Direct CO_2e emissions (fuels)	0.034 to 0.382	0.028 to 0.311	0.04 to 0.47	Market gardening: 8.6 to 14.4 Horti.: 4.3 to 6.0	Market gardening: 4.7 to 7.8 Horti.: 2.3 to 3.2	<80 hp: 669 >80 hp: 1,472	<80 hp: 1,338 >80 hp: 2,944
	Induced CO_2e emissions (upstream)	0.006 to 0.073	0.005 to 0.059	0.01 to 0.09	Market gardening: 1.1 to 1.8 Horti.: 0.6 to 0.9	Market gardening: 0.6 to 1.0 Horti.: 0.3 to 0.5	<80 hp: 73 >80 hp: 161	<80 hp: 147 >80 hp: 323
	Total	0.040 to 0.455	0.033 to 0.370	0.05 to 0.56	Market gardening: 10.1 to 15.5 Horti.: 5.1 to 6.8	Market gardening: 5.5 to 8.4 Horti.: 2.7 to 3.6	<80 hp: 742 >80 hp: 1,633	<80 hp: 1,485 >80 hp: 3,267
Unitary cost	**Investment**	€30,000 (amortised over 7 years)	5000W radiating heating panels €10,000	€43/m² ex VAT (€29 to 57/m²)	Market gardening: €7/m² Horticulture: €12/m²	€4 to 6/m² ex VAT	1 ETB passage (every 6 years): €/200/tractor	Training (every 6 years): €220
	Unit	€/animal produced			€/m²		€/hour	
	Energy savings	0.051 to 0.191	0.041 to 0.156	0.051 to 0.235	Market gardening: 2.6 Horticulture: 2.6	Market gardening: 0.9 Horticulture: 0.5	<80 hp: 0.23 >80 hp: 0.47	<80 hp: 0.47 >80 hp: 0.94
	Unit	€/animal (range: chicken for export to certified turkey)			€/m²/year		€/tractor/year	
	Total	-0.010 to +0.045	-0.042 to -0.139	-0.043 to +0.009	Market gardening: -0.2 Horticulture: 0.2	Market gardening: -1.9 Horticulture: -1.3	<80 hp: -.92 >80 hp: -222	<80 hp: -218 >80 hp: -478
Potential applicability	**Theoretical potential applicability**	All buildings All meat poultry (all supply chains) (886 million animals produced in 2010)			All greenhouses (2537 m²)		All tractors actually in use (840,000)	
	Technical criteria	No technical limitation			No specific criteria		Recent tractors (1/3 of fleet)	All tractors used
	Max. Technical Pot. Applicability (MTPA)	886 million meat poultry / year			Double screen: Market gardening: : 1,300 ha Hort.: 1,237 ha	Conventional tank: 247 ha Open buffer tank: 468 ha	<80 hp: 131,600 tractors >80 hp: 148,400	<80 hp: 394,800 tractors >80 hp: 445,200
Adoption scenario	**2010 reference situation**	Hypoth. : 5% of farms already equipped with heat exchangers, or new-generation heating equipment, or insulated in 2010 (20% in 2012)			Greenhouses already equipped: 20%	Already equipped: Market gardening: 65% Horticulture: 80%	Hypoth. : already done for 5% of tractors	Hypoth. : already applied to 5% of tractors
	Adoption scenario	In 2030: 80% of the MTPA			100% of the MTPA	promoted by aids and the cost of energy 100?% of the MTPA	80% of the MTPA	80% of the MTPA
								

Table 2

"negative", i.e. it corresponds to a saving for the farmer, for almost all the situations examined (Table 2).

• Estimation of the impact on a national scale

Maximum Technical Potential applicability (MTPA)

For the 3 sub-measures, the theoretical potential applicability corresponds to all the buildings, greenhouses and tractors in use (80% of the national tractor fleet). The potential applicability is not limited by any technical constraints:

- for poultry farms, since the 3 solutions can be implemented in all buildings, whether they have natural or dynamic ventilation and irrespective of their size;
- for greenhouses, the two solutions can be implemented in all greenhouses throughout France;
- for tractors: eco-driving concerns all tractors in France.

The only technical limitation of the potential applicability concerns ETB passage, since this is only relevant for recent tractors (estimated to account for 1/3 of the current fleet), on which the adjustments to be made will be less costly.

Measure adoption scenario

As regards the **2010 reference situation**, the default hypothesis defined (or in view of 2012 data) is that the technique is already implemented on 5% of the total number; this hypothesis is retained for the 3 "poultry building" solutions and the 2 "tractor" solutions. For greenhouses, 2011 survey data are available.

For the measure diffusion speeds, the hypotheses are:

- for poultry farms: very rapid adoption for heat exchangers (20% of buildings were already equipped in 2012; in the context of the Energy Efficiency Plan, standard supply chains are interested in this option; optimisation of the systems is making rapid progress), and rapid adoption for air heaters; the kinetics are slower for insulation as the work required is restrictive and may require the temporary discontinuation of activities;
- for greenhouses: the gradual installation of tanks is promoted by several mechanisms (see section IV) and the rise in energy prices; the same is true for thermal screens;
- for tractors: a potentially rapid adoption depends on the number of eco-driving training programmes and the development of ETBs.

IV- Results and their context

			Year 2030							Cumulative value over the period 2010-2030						
			Poultry buildings			Heated greenhouses		Tractors		Poultry buildings			Heated greenhouses		Tractors	
			A1	A2	A3	B1	B2	C1	C2	A1	A2	A3	B1	B2	C1	C2
Abatement potential ("CITEPA" method)		$MtCO_2e$	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Abatement potential ("expert" method)	Without induced emissions	$MtCO_2e$	0.065	0.053	0.079	0.052	0.028	0.230	1.379	1.098	0.802	1.202	0.696	0.376	3.481	20.89
	With induced emissions	$MtCO_2e$	0.077	0.063	0.095	0.062	0.033	0.255	1.531	1.303	0.956	1.434	0.828	0.447	3.862	23.18
Total cost for farmers		€M	1.6	-37.4	-21.27	-11.4	-0.2	-33.8	-224.5	27.1	-566.9	-322.1	-152.5	-2.9	-511.9	-3398.8
Cost per metric ton of CO_2e for the farmer ("expert" method, without induced emissions)		€/tCO_2e	25	-707	-268	-221	-8	-145	-163	-	-	-	-	-	-	-

M: million NA: data not available

Table 3

• The results

Poultry buildings:

Irrespective of the technical solution proposed, the potential unitary abatement (per animal) is higher for operations with the longest rearing periods (hence the highest gas consumptions). The lowest potentials are therefore obtained for the standard chicken supply chains and the highest for the turkey supply chain (certified and standard). The induced emissions abatement potential upstream of the farm (production and supply of energy sources) is around 10% of that for direct GHG emissions.
Irrespective of the technical solution proposed, the calculated costs are savings for the farmer, apart from certain supply chains with the heat exchanger solution. However, these savings are highly variable depending on the supply chains, and dependent on the technical solutions. Their calculation remains dependent on uncertainties with respect to the investment costs and performances in terms of energy savings, within a range of 15% to 50% in both cases. The costs of the different options would also be significantly modified by a rise - even moderate - in the price of gas (see below).

Greenhouses:

The potential abatements are higher in market gardening than in horticulture, since the energy consumptions of market gardening greenhouses are higher.
The double thermal screen is the solution permitting the greatest saving per metric ton of CO_2e avoided and the greatest reduction in direct and indirect emissions, irrespective of supply chain. The benefits of the storage tank depend more on the supply chain and the latitude; the savings decrease according to a north-south gradient.
The unitary abatement potential for emissions induced upstream varies, depending on the type of energy from 11 to 22% of the abatement potential for direct GHG emissions.

Tractors:

The savings are significantly higher for eco-driving than for the test bench, due to a potential applicability that is three times greater and an abatement factor that is twice as high (20% compared to 10%) for eco-driving. The differences in cost per tractor depending on the engine power are cancelled out when the cost is related to the metric ton of CO_2e avoided.

The fact that the majority of the options examined appear to be profitable for the farmer raises the question as to why they are not adopted; for animal buildings and greenhouses, the size of the investment and availability of cash flow may constitute an obstacle.

Comparison between sub-measures

The techniques offering the highest **abatement potential** are insulation for livestock buildings and greenhouses (double thermal screen) and eco-driving for tractors.
A comparison of the **costs per metric ton of CO_2e** avoided demonstrates that the least costly (or most profitable) technical solutions are heating equipment for poultry buildings and the double thermal screen for greenhouses; concerning tractors, the costs are very similar for eco-driving and test benches.

The different technical solutions retained for the same sub-measure can be cumulated in some instances, but if this is the case, there is no method of calculating the resulting emissions abatement (which will generally be lower than the sum of the abatements resulting from each individual technique).

• The sensitivity of the results to the hypotheses

Since the GHG emissions abatements are deduced from an energy saving expressed as a percentage of the initial consumption, the calculations are particularly sensitive to the values used for this initial reference consumption.

The abatement calculations are also dependent on the uncertainties and variability with respect to equipment performance (heat exchangers, building insulation, thermal screen, in particular) and the practices and hypotheses implemented. Hence, with tractors for example, the gas saving quantified assumes that the farmer actually applies all the eco-driving rules and engine adjustments following the ETB diagnosis.

Uncertainties concerning the evaluation of the energy saving resulting from the measure have an impact on the calculation of its cost, which is also sensitive to the hypotheses used for the price of fuels and the cost of equipment.

The variability in investment costs (around 15% to 50%) for equipment intended for poultry buildings, and a 16% increase in the price of heat exchangers (purchase + installation), for example, gives rise to a 50% reduction in the savings. However, for tractors, the prices (training and diagnostics) vary little.

The impact of energy prices on the costs of the 3 sub-measures was tested. A 10% increase (i.e. a low one) in the cost of energy generates an increase in savings that may be as high as 50% (e.g. heat exchangers for chickens). However, this is not sufficient to convert the costs into a gain for heat exchangers in standard turkey farms (costs cancelled out by a 35% increase in energy prices) or for storage tanks in ornamental horticulture.

Finally, in future years, global warming may lead to reductions in fossil fuel consumption for heating, but to an increase in water demand (evaporative cooling) or electricity demand (ventilation, air-conditioning).

• The conditions for incorporation of the measure in the national inventory

Quantification of the effects

The energy measure is taken into account in the national inventory, but it is under-estimated since the gas consumptions of greenhouses and livestock buildings are under-estimated in the CITEPA calculation. Consequently, the emission reductions quantified in this study could only actually be taken into account if the CITEPA modified its calculation conditions for these components or if the CPDP revised its gas consumption estimates for the agricultural sector.

Verifiability of implementation of the measure

Monitoring the efficacy of implementation of the technical solutions proposed depends on a number of factors:

- systematisation of the energy balances of farming operations (Dia'terre® - Ges'tim for example);
- modification of the calculation methods in CITEPA inventories (ventilation by component and energy source);
- supplementing the content of national surveys with a detailed energy component including the equipment in place and ventilation per building unit.

• The contexts and measures liable to promote the roll-out of the measure

For the last few years, the trend towards an increase in energy prices has represented a favourable context for the development of solutions enabling a reduction in the energy consumption of farms. In addition, an investment support policy has been implemented.

Poultry buildings, for example, have been able to benefit from support since 2009 via:
- the Energy Efficiency Plan (PPE that fits squarely with the second pillar of the CAP and the French Rural Development Programme), which offers support for investments generating energy savings on farms; improvements in insulation or the installation of heat exchangers are eligible investments;
- the Livestock Building Modernisation Plan (PMBE), which, in order to support the competitiveness of supply chains, can subsidise equipment improving the use of production factors.

Thanks to these state supports and the technical progress made, the installation of equipment such as heat exchangers is becoming more widespread (20% of meat poultry farms were already equipped in 2012, according to the ITAVI).

Greenhouses can benefit from:
- the Energy Savings Certificates mechanism (CEE, created by the 2005 law on energy policy), which energy sellers are obliged to acquire, helping their customers to make energy savings; hot water tanks are included in the "standard operations" of the mechanism;
- the financial aids offered (since October 2012) by FranceAgriMer to modernise greenhouses and, in particular, improve their energy efficiency; hot water tanks and thermal screens are eligible expenditures.

These mechanisms combined with rising energy prices have already encouraged the installation of tanks in greenhouses.

For **tractors**, farmers can benefit from an Energy Savings Certificate for having their tractor passed over an engine test bench.

• Other effects of the measure

The reductions in fossil energy consumption will have an impact on the other emissions produced during combustion: emissions of particles, SO_2, CO, NO_x and VOC (volatile organic compounds). The measure could therefore help achieve the reduction target (30% for particles) set as part of the second French National Health and Environment Plan and, more globally, improve air quality. However, some farmers observed an increase in dust in the air with heat exchangers, detrimental to their health and that of the poultry.

• Conclusions

For this assessment of the GHG emissions abatement potentials through reduced energy consumption, only technical solutions for which the efficacy has been proven and quantified were retained. Other techniques - sometimes simpler and more economical - exist (cleaning temperature sensors, adapting engine power to the work to be carried out, etc.); these could not be examined since no method of quantifying their efficacy is available. Changes in livestock farming practices (starting off in a brooding house, for example) could also generate substantial energy savings. But, although they are recommended in Good livestock practice guidelines, these options have not been the subject of any assessment.

The highest abatement potentials calculated are obtained for tractors, but they assume optimum farmer behaviour (compliance with eco-driving rules and adjustment of tractors after passing them over a test bench). For the other two sub-measures, the performance is lower but not related (or much less so) to farmer behaviour. Furthermore, for the majority of the sub-measures proposed, application of the techniques selected generates financial savings for the farmer, which are sometimes very substantial.

Finally, in accordance with the specifications of this study, only supply chains and sectors consuming fossil energy on the farm (and hence emitting GHGs on the farm) were considered. A study aimed at quantifying the energy savings in the agricultural sector, all energy forms combined (including electricity) would, by its very nature, lead to different conclusions.

Part III

Comparative analysis and conclusion

5. Comparative analysis of the ten measures proposed

5.1. Cumulative abatement of all the measures and sub-measures

● Calculation assuming the additivity of measures and sub-measures

Assuming their additivity, and applying the calculation methods used by the CITEPA for the national inventory in 2010, the cumulative annual abatement excluding induced emissions for all the measures is 10 Mt CO_2e per year in 2030. The abatement calculated in this way represents 9.5% of 2010 emissions from the agricultural sector (including fossil energy consumption, but excluding LULUCF), which amounted to105 Mt CO_2e (CITEPA 2012).

The calculation equations used by the CITEPA for the inventory of national emissions follow the international recommendations. By their very nature, some of these equations are not capable of taking into account the expected abatement of some of the measures or sub-measures proposed in this study. This is the case for measures promoting carbon storage in soil and biomass without any change in land use, such as no-till or agroforestry. It is also the case for the emission sources calculated using standard values, such as enteric methane emissions from ruminants, meaning that it is not possible to reflect the proposed modifications to their diet. Changes are under way, thanks to studies leading to proposals designed to more accurately take into account the effect of agricultural practices in the national inventory ("Mondferent"[14] project for enteric methane emissions, for example) but their incorporation in the inventory requires prior international validation. By its nature, the CITEPA calculation method used for the 2010 inventory therefore under-estimates the expected overall abatement from the measures and sub-measures analysed here.

It is for this reason that a second calculation method was used by the experts. The annual abatements in 2030 for all the measures and sub-measures, estimated using the alternative calculation method proposed by the experts, are summarised in Table 1. For the measures or sub-measures for which several alternative technical options were explored, only one of these was reported (tilling one year in five for the No-till measure, for example).

With the calculation method proposed by the experts - still assuming their additivity - the cumulative annual abatement resulting from the measures and sub-measures, excluding induced emissions, is 32.3 Mt CO_2e per year for 2030, i.e. three times higher than the previous calculation. This second figure cannot be compared with the agricultural emissions calculated within the framework of the national inventory since the calculation methods differ. To make such a comparison, it would be necessary to recalculate the agricultural emissions for 2030 using the calculation methods proposed by the experts, a calculation that could not be performed within the short time-frame available for this study.

[14] The objective of the "Mondferent" project is to improve the method for estimating enteric methane emitted by cattle in order to improve the reliability of the calculations performed for the inventory (INRA-MAAF convention).

● Calculation test taking into account interactions between measures and sub-measures

The implementation of a measure or sub-measure may modify the abatement potential and/or cost of another measure or sub-measure, due to interactions. These modifications may concern the potential applicability (the implementation of a measure modifies the potential applicability of another measure: increasing legume surface areas reduces the potential applicability of the measure concerning nitrogen fertiliser application, for example) and/or the abatement potential or the unitary cost (the implementation of a measure modifies the value of the variables used to calculate the abatement potential or cost of another measure: for example, the reduction in mineral nitrogen doses related to better adjustment of yield targets reduces the quantity of mineral nitrogen that can be saved by introducing a nitrification inhibitor). The effect of incorporating these interactions on the overall abatement potential also depends on the order in which the measures and sub-measures are implemented: for example, if no-till systems is applied first, it is not then possible to introduce more legume crops (peas, in this case) into arable land, since peas require tillage; conversely, introducing legume crops first limits the implementation of no-till farming. A number of calculation hypotheses are possible therefore. The method that was used here first calculates the interactions between sub-measures within a measure, followed by the interactions between measures, assuming that the measures affecting cropping sequences or systems are implemented first.

The measures presenting "internal" interactions between sub-measures are the Fertiliser Application, Energy Savings, and Methanisation and flares measures. For the first two, the interactions concern the reference input consumptions. Hence, the reference mineral fertiliser dose applied to each crop decreases successively following adjustment of the yield target, then incorporation of the amount of organic nitrogen supplied, elimination of the first application, introduction of a nitrification inhibitor and, finally, more accurate localisation of fertiliser applications. Similarly, the reference natural gas consumption of farms decreases successively following the installation of insulation, then heat exchangers and, finally, a new heating system. For biogas plants and flares, the interaction affects the potential applicability of the sub-measures, i.e. the number of plants on which they can be implemented. The calculations of these interactions are provided in the report. Ultimately, taking into account the within-measure interactions, the total abatement potential falls from 32.3 Mt CO_2e per year to 31.5 Mt CO_2e per year for 2030.

The interactions between measures mainly concern the potential applicability (for example, the surface areas occupied by grass buffer strips and hedges are no longer concerned by fertilisation management), but also, in some cases, "inputs" (animal manure produced on grassland when the grazing period is extended is no longer available for methanisation). To assess the impact of these interactions on the annual abatement potential in 2030, three steps were implemented. The reference cropping plan was re-calculated following application of the sub-measures relating to Legume crops on arable land, Agroforestry, Hedges and Green buffer strips. The maximum technical potential applicability obtained in 2030 was then re-calculated for each of the other sub-measures, using the technical criteria employed by the experts to determine the MTPA. Finally, the average unitary abatement potentials of the different sub-measures were applied to these new scopes. The "input" interactions were considered for measures concerning fertilisation and livestock manure.

When these two calculations are applied - i.e. when within-measure and then between-measure interactions are incorporated -, the cumulative abatement potential for all the sub-measures falls from 32.3 to 29.6 $MtCO_2e$ per year, i.e. a reduction of 8%. The use of two other calculation methods (implementation of sub-measures by increasing order of costs or by decreasing order of abatement potentials) leads to greater decreases and hence lower cumulative abatement potentials; the orders of magnitude are nonetheless similar, at 26.6 and 28.4 $MtCO_2e$, respectively.

In total, incorporating interactions between measures and sub-measures reduces the cumulative abatement potential by 8 to 18% depending on the calculation method adopted. This relatively low reduction percentage can be explained by the fact that the measures and sub-measures proposed concern a specific diversity of units and practices (arable production, livestock production, manure management, etc.) and hence without major "overlaps".

	Sub-measures	Annual abatement potential (in Mt CO_2e per year) in 2030
Reduce mineral nitrogen fertiliser applications		
❶	A. Reduce the rate of mineral fertiliser by more effectively adjusting yield targets	2.60
	B. More effectively replace synthetic mineral nitrogen with nitrogen from organic products	1.88
	C1. Delay the date of the first fertiliser application in the spring	0.42
	C2. Use nitrification inhibitors	0.61
	C3. Incorporate into the soil and localise fertilisers	0.58
❷	A. Increase the surface areas of grain legumes on arable farms	0.91
	B. Increase and maintain legumes in temporary grassland	0.48
Store carbon in soil and biomass		
❸	Switch to occasional tillage, 1 year in 5	3.77
❹	A. Develop cover crops sown between two cash crops in arable farming systems	1.08
	B. Introduce cover cropping in vineyards and orchards	0.14
	C. Introduce grass buffer strips alongside water courses or around the edges of fields	0.30
❺	A. Develop agroforestry with a low tree density	1.53
	B. Develop hedges around the edges of fields	1.25
❻	A. Extend the grazing period	0.20
	B. Increase the lifespan of temporary sown grassland	1.44
	C. Reduce nitrogen fertiliser application on the most intensive permanent and temporary sown grassland	0.46
	D. Improve low productive permanent grassland by increasing livestock density	0.45
Modify the diet of livestock		
❼	A. Replace carbohydrates with unsaturated fats in diets	1.89
	B. Incorporate an additive (nitrate-based) in diets	0.48
❽	A. Reduce the protein content in the diets of dairy cows	0.23
	B. Reduce the protein content in the diets of pigs and sows	0.48
Recycle manure to produce energy, reduce fossil fuel consumption		
❾	A. Develop methanisation	5.78
	B. Cover storage pits and install flares	3.40
❿	A. Reduce fossil fuel consumption for heating livestock buildings	0.20
	A. Reduce fossil fuel consumption for heating greenhouses	0.08
	C. Reduce the fossil fuel consumption of agricultural machinery	1.61
Total	(assuming additivity)	32.3

Table 1. Annual abatement potential (in Mt CO_2e per year) of the sub-measures examined, for the year 2030, excluding induced emissions (calculation using the method proposed by the experts)

5.2. Incorporation of abatements induced upstream and downstream

The main objective of the study was to assess the abatement resulting from the implementation of the measures and sub-measures proposed for the emission sources occurring within the farm and in physically linked areas (N_2O emissions related to denitrification in wet zones following the transfer of nitrate from agricultural fields, for example). The modifications in emissions induced upstream or downstream related to the purchase or sale of goods modified by the measure (CO_2 emissions related to the production of synthetic mineral fertilisers, CO_2 emissions avoided thanks to the production of energy on the farm, for example) were nonetheless also quantified for the major emission sources.

Figure 1 shows the abatement calculated for the year 2030, with or without induced emissions, for all the measures. The greatest deviations from the bisector are observed for the Fertiliser application, Agroforestry and hedges, and Legume crops measures (above the bisector) and the Fats/additives measure (below the bisector). The details per sub-measure (not shown on the graph) reveal that the abatement calculated is reduced when the induced emissions are included in just three cases (Fats in the diets of cattle, Intensification of unproductive grassland and cover cropping). Implementation of these 3 sub-measures actually increases the emissions induced upstream of the farm. In a very large number of cases, the abatement calculated is not modified since the sub-measure has no or very little effect on the induced emissions (Agroforestry, Flares, etc.). The incorporation of induced emissions, however, significantly increases the abatement calculated for the sub-measures relative to nitrogen fertiliser application, legumes and nitrate additives in animal feed. This can be explained by the GHG emissions related, firstly, to the production of mineral nitrogen fertiliser and, secondly, to the production of soybean used in animal feed. For the Fertiliser application, Legume crops and Nitrogen content of animal feed measures, the abatement related to the induced emissions represents 45%, 91% and 85%, respectively, of the direct and indirect emissions abatement. Incorporation of induced emissions increases the benefits of the measure in these three cases. Conversely, for the fats sub-measure, incorporating induced emissions reduces the value of the measure since replacing carbohydrates in feed rations (from cereals) with fat-rich raw materials leads to an increase in upstream emissions. For the other sub-measures, the effects on induced emissions upstream or downstream are low and not incorporating them has little effect on the abatement calculated.

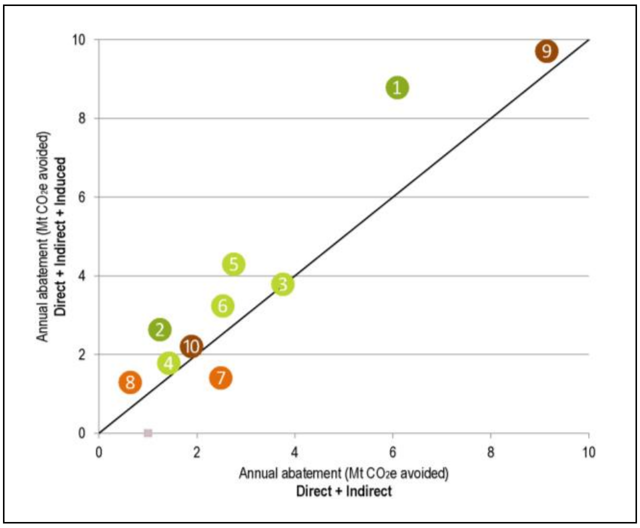


Figure 1. Total annual abatement per measure, including induced emissions as a function of the abatement excluding induced emissions (in Mt CO_2e per year, calculation for the year 2030, calculation method proposed by the experts)

1 Fertiliser application
2 Legume crops
3 Tillage 1 year in 5
4 Planting of cover
5 Agroforestry and hedges
6 Grassland management
7 Fats and additives
8 Protein content of feed
9 Methanisation and flares
10 Energy savings

5.3. Calculations of costs of measures and sub-measures, with or without state subsidies

The costs of the measures and sub-measures were calculated using two methods, including or otherwise state subsidies. The subsidies considered here are only those that cannot be separated from the prices in operation (subsidy when the electricity produced by methanisation is bought and tax exemption for agricultural fuels). "Optional" subsidies, such as SPEs (Single Payment Entitlement), coupled aids and regional subsidies, are totally excluded from the cost calculations. A positive cost represents a shortfall for the farmer. Conversely, a negative cost represents a gain, generally related to input savings. For the majority of the sub-measures, whether or not subsidies are included, does not modify - or if it does, only very slightly - the cost calculation per metric ton of CO_2e avoided. However, the difference is greater for the Methanisation sub-measure, due to the subsidised purchase of the electricity produced. It is also marked for the measures or sub-measures involving high direct energy consumptions given the implicit subsidy represented by the tax exemption on agricultural fuel. For the Methanisation sub-measure, the cost to the farmer per metric ton of CO_2e increases from €17.3 with subsidies to €54.9 excluding subsidies. Conversely, for occasional tillage, the price per metric ton of CO_2e avoided decreases from €7.9 with tax exemption on the fuel to -€12.9 ignoring this tax exemption. Similarly, for the reduction in the fuel consumption of agricultural machinery, the cost per metric ton of CO_2e avoided falls from -€164 with the tax exemption to -€317 without the tax exemption.

5.4. Incorporation of private transaction costs

Private transaction costs (PTCs) correspond to the time spent by the farmer finding information, obtaining training and completing administrative documents relative to a measure. Table 2 presents the PTCs calculated per hectare for the sub-measures supported by existing agri-environmental measures, for which the calculation model used has been validated. These values are given by way of indication only. In particular, the fact that PTCs reduce over time as a result of the learning effect was not taken into account.

The PTCs calculated vary from €9 to €72 per hectare for the 12 sub-measures for which the calculation formula has been validated; they are negligible for grass buffer strips. They are also negligible for cover crops in vulnerable zones (not indicated in the table), since these measures are part of "Good agricultural and environmental practices" and are already compulsory.

Overall, it appears that the PTCs are of the same order of magnitude as the costs calculated excluding PTCs. Some sub-measures with a negative cost excluding PTCs have a cost that becomes positive when the PTCs are taken into account (the reduction in N fertiliser dose by adjustment of yield targets, for example). This may explain why some measures and sub-measures are not spontaneously implemented despite a negative cost excluding PTCs. This point will be discussed again later on. Hereafter, given that it is impossible to calculate the PTCs in a homogeneous manner and with the same level of precision for all the sub-measures, the analysis will be conducted on the basis of costs excluding PTCs.

	Costs (€/ha/year)	**Cost of the sub-measure excluding PTC**	**PTC**	**Cost of the sub-measure with PTC**
Fertiliser application	Reducing the dose by adjusting yield targets	-9	18	9
	Organic fertiliser application	-12	18	6
	Date of nitrogen application	-23	19	-4
	Localisation of fertiliser application	-9	19	10
Leguminous crops	Legumes on arable farms	19	25	44
	Legumes on grassland	-31	39	8
No-till		3	17.3	20.3
Planting of cover	Cover crops (in non-vulnerable zones)	41	16	57
	Cover cropping in vineyards/orchards	10	72	82
	Green buffer strips	633	negligible	633
Grassland management	Grazing period	-26	9	-17
	Intensification	-4	19	15

Table 2. Costs (in €/ha/year), with or without incorporation of private transaction costs (PTCs), of the twelve sub-measures for which they could be calculated (a positive cost represents a cost to the farmer, while a negative cost represents a saving)

5.5. Comparative costs and abatements of the measures and sub-measures

Figure 2 shows the cost excluding PTCs for each sub-measure, expressed in euros per metric ton of CO_2e avoided (y axis) as a function of the cumulative abatement expressed in Mt of CO_2e avoided (x axis); the sub-measures are ranked in increasing order of cost. For each sub-measure, the height of the rectangle indicates the cost per metric ton of CO_2e avoided and the width of the rectangle the emissions abatement (in Mt of CO_2e avoided per year) calculated on the basis of the potential applicability achieved in 2030.

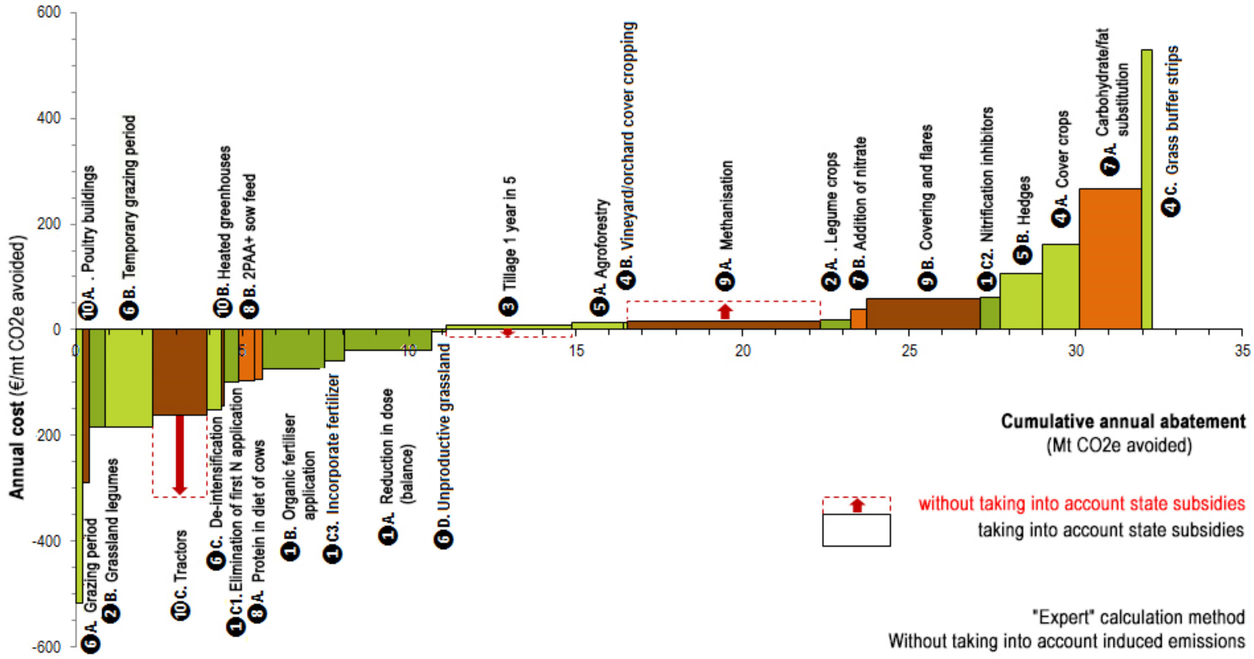


Figure 2. Cost (in euros per metric ton of CO_2e avoided) and annual abatement potential in 2030 on a mainland France scale (in Mt of CO_2e avoided per year) of the sub-measures examined

Cost calculated including - or otherwise - the subsidies that cannot be separated from the price paid or received by the farmer, but excluding private transaction costs. Abatement calculated excluding induced emissions, using the calculation method proposed by the experts, without taking into account interactions between measures

The cost represented is the saving (negative cost) or shortfall (positive cost) for farmers (not including private transaction costs), calculated including state subsidies that cannot be separated from prices. In the case of sub-measures for which the calculation with and without the subsidy gave a significantly different result, the cost calculated excluding the subsidy is indicated by the dotted line. The abatement is calculated excluding induced emissions, with the calculation equations proposed by the experts, assuming additivity and without taking into account interactions between measures and sub-measures.

The cumulative total on the x-axis, which corresponds to implementation of all the sub-measures, is 32.3 Mt CO_2e per year, as indicated previously. The range of costs per sub-measure is from -€500 to +€500 per metric ton of CO_2e avoided.

Using this graph, the expected overall abatement potential can be broken down into three parts:

● **The first third of the expected overall abatement corresponds to sub-measures with a negative cost**, i.e. leading to a financial saving for the farmer (with the hypotheses adopted here). These are mainly sub-measures involving technical adjustments with input savings and no loss of production output. This category includes sub-measures relative to grassland management (extension of grazing period, increase in proportion of legumes in grassland, extension of lifespan of temporary grassland, making the most intensive grassland less intensive), sub-measures designed to generate fossil fuel savings (adjustment of tractors and eco-driving, insulation and improvement of greenhouse and livestock building heating systems), adjustment of nitrogen fertilisation by application of the balance method, adaptation of application dates and placement, more effectively taking into account nitrogen supplied by organic products, adjustment of the amount of protein in the diet of animals (ruminants and monogastric animals). Nitrogen management, in crop production (via fertilisation of crops and grassland, the inclusion of legumes in grassland) and livestock production (via feed) accounts for the greatest share of the abatement potential associated with this first third. Then come grassland management and fossil fuel savings.

● **Another third of the expected overall abatement potential corresponds to sub-measures with a moderate cost (less than 25 euros per metric ton of CO_2e avoided)**. This category includes sub-measures requiring specific investments (methanisation, for example) and/or associated with a slightly greater modification of the cropping system (reduced tillage, agroforestry, legumes) that may potentially lead to moderate reductions in production outputs (-2.1% with occasional tillage, for example), partially offset by a reduction in costs (fuels) or economic outlets for additional products (electricity, wood). The abatement potential of these sub-measures is high, but its calculation is highly sensitive to hypotheses relative to the potential applicability (Agroforestry, Methanisation, for example) and/or the technical options retained. Thus the abatement calculated for no-till, for example, varies from 0.9 Mt CO_2e per year for the superficial tillage option to 5.8 Mt CO_2e per year for a continuous direct seeding option (data not shown). The relatively modest cost of the Methanisation sub-measure is linked to the fact that the state subsidy is taken into account in the purchase price for the electricity produced; excluding the subsidy, this cost rises from €17.3 to €54.9 per metric ton of CO_2e avoided. Conversely, a calculation without the subsidy represented by the tax exemption status of agricultural fuels increases the value of occasional tillage: the cost of this sub-measure even becomes negative, falling from +€7.9 to - €12.9 per metric ton of CO_2e avoided.

● **The third part of the expected overall abatement potential corresponds to sub-measures with a higher cost (greater than 25 euros per metric ton of CO_2e** avoided). This category includes sub-measures requiring an investment with no direct financial return (Flares, for example), the purchase of specific inputs (Nitrification inhibitor, Unsaturated fats or additives incorporated into the diet of ruminants, for example), dedicated labour time (Cover crops, Hedges, etc.) and/or involving greater production losses (grass buffer strips reducing the cultivated surface area, for example), with no or little reduction in costs and/or economic outlets for the additional products generated. The calculation was made assuming that the production of cover crops or grass buffer strips has no outlets, leading to the costs of the two sub-measures being over-estimated.

Figure 3 is a simplification of the previous figure. It presents the cost per metric ton of CO_2e avoided as a function of the abatement potential of each of the measures, with each measure combining the sub-measures related to a same technical lever, assuming that they are additive. This graph demonstrates the following:

● The measure levers concerning fossil energy savings, grassland management, nitrogen content of livestock feed, the development of legumes and the management of nitrogen fertiliser application represent an overall abatement potential of around 12.6 Mt CO_2e per year at a negative cost (of -€175 per metric ton of CO_2e avoided for the Grassland measure to -€59 per metric ton of CO_2e avoided for the Fertiliser application method). The "nitrogen fertiliser application" lever accounts for almost half of this total abatement potential (6.1 Mt CO_2e). To this can be added the Legumes measure and a proportion of the Grassland measure (De-intensification of the most intensive grassland sub-measure), for which the expected abatement is also derived from a reduction in the use of nitrogen fertilisers. Managing the nitrogen content of the diet of livestock represents a low abatement potential (0.7 Mt CO_2e), which can be explained by the fact that significant progress has already been made in this area (biphase feeding in pig farms) and that reducing the nitrogen content of manure only has an indirect effect on GHG emissions following conversion of ammonia nitrogen into N_2O. Limiting NH_3 emissions by volatilisation nonetheless helps to reduce overall nitrogen losses and is of significant importance in terms of air quality. The Legumes measure represents an abatement potential of 1.4 Mt CO_2e, which is lower than some of the figures sometimes put forward, but this can be explained by the fact that the study did not consider all the possibilities in terms of species selection. Neither did it consider an increase in fodder legume surface areas (clover, alfalfa, etc.), which requires simultaneous modification of livestock systems - a hypothesis outside the scope of the study. Were more significant changes to production systems and livestock feeding methods to be considered, the legumes lever could be significantly more important. In total, the management of nitrogen on arable land, grassland and in animal nutrition contributes to almost 70% of the abatement potential with a negative cost. This high percentage can be explained by the importance of the potential applicability concerned by several of these sub-measures and by the weight of N_2O in agricultural emissions, related to its GWP. In addition, the incorporation of emissions induced upstream of the farm (related to the energy required for the production and transport of synthetic nitrogen fertilisers) further reinforces the value of measures or sub-measures concerning nitrogen management (see section 5.2). In addition to nitrogen management, the other lever for the reduction of GHG emissions with a negative cost is control of fossil energy consumption on the farm.

● The Occasional tillage, Methanisation and flares, Agroforestry and hedges measures represent an abatement potential of 15.8 Mt CO_2e per year for a cost varying between €8 and €56 per metric ton of CO_2e avoided. As already indicated, the abatement potential calculated is highly dependent on the hypotheses made concerning the unitary abatement (Occasional tillage, Agroforestry and hedges) and on the potential applicability reached in 2030 (Methanisation and flares, Agroforestry and hedges). In addition, the cost depends greatly on incorporation or otherwise of state subsidies for the Methanisation and Occasional tillage measures (see Section 5.3).

● The Cover crop and grass buffer strip and Fats and additives in the diets of ruminants measures represent an abatement potential of 3.9 Mt CO_2e per year in 2030, with a cost of €220 per metric ton of CO_2e avoided. For the Cover crops, and grass buffer strips measure, the cost is related to the dedicated cultivation operations and/or production losses; in the context of this study, the entire cost was related to the GHG emissions abatement whereas the objectives associated with these practices are broader than simply reducing GHG emissions: reduction of nitrate concentrations in water, protection against erosion, maintenance of biodiversity. For the Fats/additive in cattle feed measure, the cost is related to the raw materials added to the rations, in particular for the Fats sub-measure. In this second case, the measure does not present any other benefits in addition to the reduction of enteric methane emissions, other than an improvement in the nutritional content of products (higher omega 3 content).

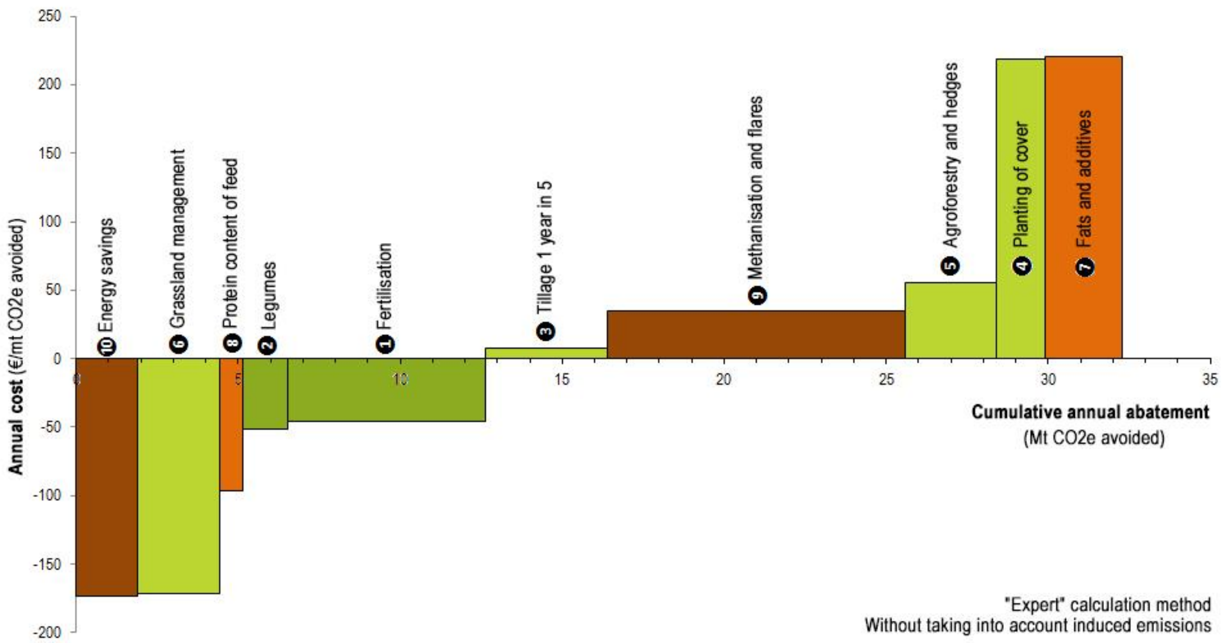


Figure 3: Cost (in euros per metric ton of CO_2e avoided) and annual abatement potential in 2030 on a mainland France scale (in Mt of CO_2e avoided per year) of the measures examined

Cost calculated including the subsidies that cannot be separated from the price paid or received by the farmer, but excluding private transaction costs. Abatement calculated excluding induced emissions, with the calculation method proposed by the experts, without taking into account interactions between measures.

5.6. Comparison with other international studies

Comparison of the results of this study with those obtained in similar studies conducted in other countries (see bibliography for section 1) is difficult since the criteria used to select the measures, the abatement and cost calculation scopes and the agricultural contexts differ (Eagle et al., 2012 for the USA; Moran et al., 2008, 2011 for the UK; Schulte & Donnellan, 2012 for Ireland; Bellarby et al., 2012 for Europe; McKinsey & Company, 2009 for the world). However, convergences do nonetheless emerge.

The assessment of the total abatement potential relative to the reference emissions is comparable to those obtained in other countries using a similar approach. For example, the abatement potentials represent 2 to 11% of the reference emissions in the Canadian study, 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, caution is required when making comparisons of this type given the differences in scope, context, reference scenarios and emission calculation methods, as well as the sensitivity of these results to the number and nature of the measures examined.

One of the common features of the studies that assessed unitary abatement costs (McKinsey & Company, 2009; Moran et al., 2011; Schulte et al., 2012) is that they demonstrate a series of measures with negative or moderate costs. The results of the present study thus confirm that a large proportion of the abatement potential in agriculture can be obtained without affecting the profitability of agricultural activities - in fact, sometimes even increasing it - with the reduction in GHG emissions and savings achieved in these cases being related to the input savings generated by technical adjustments (fertiliser application, for example). Several measures or sub-measures falling into this category emerge in all the studies. This is the case for nitrogen fertiliser application, reduced tillage methods and grassland management. The quantifications made corroborate the conclusions reached in the present study as regards 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 range of unitary costs obtained in the French study (from -€ 515 to € 529 per tCO_2e) is comparable to that obtained in the Irish and Canadian studies. It is much narrower than that obtained in the British study, which considered more "prospective" measures (use of ionophore antibiotics, for example).

Classification of the measures examined in the study conducted by MacKinsey & Company is consistent with that obtained in the present study for several aspects (relative positioning of measures concerning fertiliser applications and feed additives, for example), although the absolute values are not comparable due to differences in calculation scope. Some of the measures examined appear in other studies, but not all of them. This is the case for the measures targeting 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 tackled solely in the French study.

However, some measures examined in other studies were not considered in the French study. This is the result of a different agricultural context (rice-growing, for example), or a measure selection method based on alternative criteria. Measures involving banned technologies or ones which are not very socially acceptable are excluded from the French study, whereas they were included in other studies (use of ionophore antibiotics or vaccines against methanogens). Similarly, levers that are promising in the long term but which are still in the research stage were not examined (animal selection aimed at reducing methane emissions, for example).

Overall, in view of the other studies of the same type conducted internationally, the present study appears to be more "conservative" than others, in that only "conventional" technical levers that are available and easy to implement were explored (for example fertiliser application, soil tillage, legumes, etc.). The benefit of this choice is that the abatement and cost calculations performed are probably more robust than in the other studies since they concern practices that are well documented. However, this characteristic suggests the need to update the study once additional knowledge has been acquired relating to some levers that were not examined (Box 1).

Finally, one of the major contributions of the French study is that it puts the sensitivity of the results to the emission and cost quantification method ("CITEPA" or "expert" calculation, incorporation or otherwise of induced emissions, incorporation or otherwise of state subsidies, etc.) into perspective when assessing the abatement potentials and costs. This aspect - largely absent from existing studies - opens up avenues for the improvement of emissions inventories and highlights the importance of having a statistical framework capable of incorporating the environmental effects of farming practices.

5.7. Uncertainties, sensitivity and robustness of the study results.

All the available scientific and technical data were mobilised in order to perform the abatement and cost quantifications required for this study as accurately as possible. However, these quantifications are often associated with a high level of uncertainty.

● Firstly, the unitary abatement and cost values used (per hectare, per animal, per nitrogen unit applied, etc.). For the abatement calculated using the calculation method proposed by the experts, the equations and values used stem from the most recent IPCC recommendations or are taken from the international scientific literature, favouring - where these exist - meta-analyses proposing robust values based on numerous trials (No-till, for example) and ensuring that values adapted to French conditions are used. However, the processes involved (N_2O emissions by soil, carbon storage/release in soils and biomass, CH_4 emissions by livestock) are highly dependent on local conditions (soil types, climate, livestock farming systems, etc.) and demonstrate significant variability in terms of space and time As a result, the values adopted are associated with a high level of uncertainty. For the unitary costs, the economic data used are those for 2010, in the absence of access to sufficiently detailed scenarios for the evolving socio-economic context providing information on all the variables required to make calculations over the period 2010-2030. Once again, some of the prices used (prices of energy, fertilisers, raw materials for animal feed, agricultural products) are liable to vary significantly over time and between areas. For some measures (Fertiliser application, No-till, Agroforestry, Grassland management, Protein content of animal feed), the quantitative hypotheses were made relative to the effect (or its absence) on yields, to which cost calculations are highly sensitive.

● Determination of the maximum technical potential applicability (MTPA). Primarily technical criteria (crops grown, soil depth, useful water reserve, stoniness, degree of hydromorphism, field size, livestock category, manure volumes, etc.) were used to estimate the potential applicability to which the measure or sub-measure could be applied without any major technical obstacles. This estimation is associated with uncertainty since the technical obstacles identified and their relative weights are not independent of the economic context or the technological and organisational choices favoured (individual or collective methanisation, for example).

● Determination of the adoption kinetics over the period 2010-2030, and of an MTPA percentage attained in 2030. For measures or sub-measures related to technical adjustments, the adoption kinetics may be relatively rapid and it was considered that 100% of the MTPA could be attained by 2030. Conversely, for measures assuming a greater change in production methods and working conditions (Agroforestry, Methanisation, for example), the adoption kinetics were considered to be slower. For Agroforestry, for example, it was considered that between 4 and 10% of the MTPA could be achieved by 2030. For methanisation, 33% of the MTPA was retained for 2030. The abatement potential calculated in 2030 for these measures is highly sensitive to these hypotheses.

Box 1. A review of the measures not examined

A number of measures capable of reducing GHG emissions from the French agricultural sector were not examined in the context of this study. The measures not examined - along with the reasons for not examining them - are indicated in the full report. These measures were divided into four categories.

● *Measures presenting risks, the social acceptability of which was judged to be poor, or measures not authorised in the European Union*

The abatement potential associated with these measures (use of antibiotics to regulate methanogen populations in the rumen, for example) has been assessed in studies conducted in other countries. In the present study, it was decided to automatically eliminate this type of solution. The question was raised for the sub-measure targeting a reduction in methane via the addition of nitrate to feed rations. The social acceptability of this sub-measure may be poor due to the negative connotation of the term "nitrate", and it could pose a risk to livestock if incorrectly managed. This sub-measure was nonetheless examined.

● *Measures presenting a limited abatement potential due to the low significance of the sector in French agriculture.*

Several measures, often cited in similar conditions conducted in other countries, were not examined in this study because the surface areas or livestock numbers concerned are low in the French agricultural context compared to other sectors. This is the case, for example, for measures aimed at reducing CH_4 emissions in the rice-growing sector, protecting organic soil or restoring biomass production on degraded soil to promote carbon storage. Similarly, within certain measures, in order to concentrate quantification efforts on dominant sectors, quantification of the abatement and cost was not performed for certain minority sectors (beef cattle and poultry for the measure concerning the nitrogen content of animal feed, sheep and goats for the Fats/additives measure, fossil energy consumption in buildings housing pigs and cattle for the Energy saving" measure, etc.). The decision to target quantification efforts on measures that theoretically offer a high abatement potential in the French agricultural context and, within the measures examined, to concentrate on dominant sectors, should in no way disqualify the efforts already made - or which may be made in the future - to reduce GHG emissions in other sectors. Ensuring that measures implemented to reduce GHG emissions by the agricultural industry are transparent to society requires a coordinated effort on the part of all the supply chains involved.

● *Measures requiring additional knowledge and/or technical references in order to assess the feasibility and value*

A number of measures were not examined - although some were presented as being promising in the literature - because additional knowledge is still required in order to be able to assess their value and quantify their abatement potential. In general, these measures are the focus of active research. They include the incorporation of stable charcoal into soils (biochars), for which the overall environmental value needs to be assessed, modification of the physicochemical conditions and/or microbial communities of soils to reduce N_2O emissions, the use of microbial strains associated with legumes with a capacity to reduce N_2O into N_2,the genetic improvement of plants targeting their capacity to absorb nitrogen from the soil, or the genetic improvement of livestock to reduce methane emissions per animal and/or product unit, and the production of biohydrogen by fermentation from livestock manure.

In the livestock farming sector, very active research programmes are under way focusing on the possibility of directly or indirectly selecting cattle on the basis of enteric CH_4 emissions. A number of teams in Europe and Oceania are currently exploring the genetic variability of CH_4 emissions and the early results are encouraging. Early heritability estimates assign moderate values ($h^2 = 0.20$) and a good level of variability, making selection possible and offering hope of being able to achieve a -25% reduction in CH_4 emissions in 10 years in dairy cows. Scientific advances are rapid and measurement methodologies are improving: it is currently possible to have access to direct CH_4 measurement systems - still experimental - that can be used in milking parlours and/or on grass, at acceptable costs. But numerous points remain to be validated before it will be possible to envisage incorporating this trait in selection processes. The interest of these avenues lies in their potentially extensive potential applicability. However, it will be at least a decade before operational results emerge from the research being conducted in this field.

● *More structural measures concerning the nature and location of agricultural production systems, the organisation of the food chain and consumption*

The study specifications stipulated that the measures proposed must concern agricultural practices, without any major modification to production systems, their location and production levels. The demarcation between these two types of measures (measures concerning techniques, on the one hand, and production systems, on the other) is open to debate since the majority of technical measures have repercussions on the organisation of farms. This is particularly true for measures concerning cropping systems (legumes, for example), grassland management or agroforestry, at the limit of the study specifications. Other measures, based on more radical changes in production methods (organic farming, for example) and the location of production (re-combination of arable and livestock farming) or supply and dietary modes (local channels, reduction in the production of animal products) were not examined, since they are outside the scope of this study. These more structural options remain to be investigated.

Depending on the measures or sub-measures studied, the sources of uncertainty may stem primarily from one of these aspects, or from several of them (Table 3). For measures or sub-measures concerning technical adjustments (fertiliser doses or application methods, adjustment of feed rations, consumption of fossil energy, etc.), the unitary abatements are generally well documented, but they are extremely variable over time and space (N_2O emissions, for example). The scope calculations are relatively precise since they concern cultivated surface areas, animal numbers, tractor numbers, etc., for which statistical data are available. In general, it was considered that 100% of the MTPA would be attained by 2030 for these sub-measures. For measures assuming a slightly greater modification in the organisation of the farm (No-till, Agroforestry, Methanisation), the uncertainty regarding the potential applicability and adoption kinetics is higher. Table 3 provides a qualitative summary of the levels of uncertainty regarding the unitary abatement potential, unitary cost, potential applicability and adoption kinetics. Figure 4 shows the cost per metric ton of CO_2e avoided in 2030 and the annual abatement potential for all the measures, these being associated with a range (low, moderate and high values). The range concerning the abatement potential is particularly high for the No-till, Methanisation and flare, Fertiliser application and Agroforestry and hedges measures.

	Uncertainty with respect to unitary abatement (excluding induced emissions)	Uncertainty with respect to unitary cost	Uncertainty with respect to MTPA and adoption
❶ Fertiliser application	***	**	**
❷ Legume crops	***	**	**
❸ No-till	****	**	**
❹ Planting of cover	**	*	*
❺ Agroforestry and hedges	****	**	****
❻ Grassland management	***	**	***
❼ Fats and additives	*	**	*
❽ Protein content of feed	**	***	*
❾ Methanisation and flares	*	**	****
❿ Energy savings	*	**	**

Table 3 Evaluation of uncertainty relative to abatement and unitary cost
(****: very high uncertainty, ***: high uncertainty, **: moderate uncertainty *: low uncertainty)

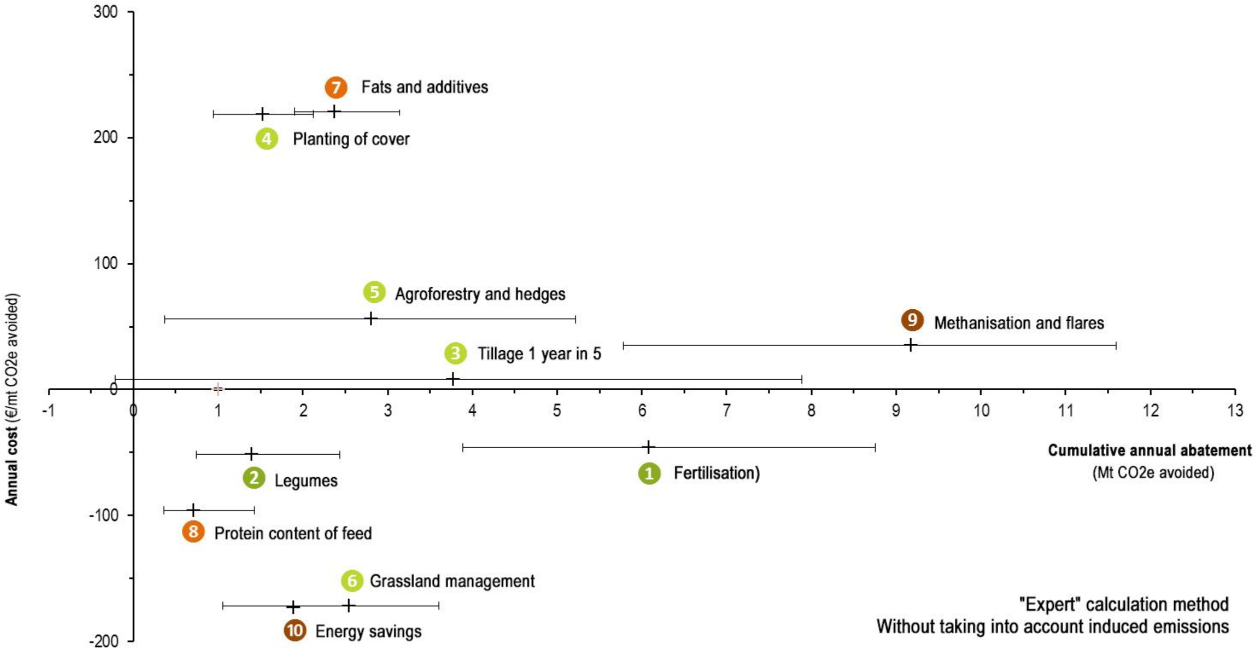


Figure 4. Uncertainty margins relative to the annual abatement potentials of the measures (in 2030)
(low, moderate, high values)

6. Summary and conclusion

Assuming that they are additive, the overall annual abatement potential for GHG emissions from the agricultural sector related to the implementation of all the measures proposed in this study would be 32.3 Mt CO_2e per year in 2030, excluding induced emissions. This overall abatement potential is reduced by 8 to 18%, depending on the calculation method, and if interactions between measures are taken into account. The figures then would be between 26.5 and 29.7 Mt CO_2e per year.

In the event of implementation of these measures, comprehensive quantification of the abatement by the national inventory would assume a major change in the inventory methods, particularly to incorporate the effect of measures leading to increased carbon storage in the soil and biomass (No-till systems, Grassland, Agroforestry, Cover crops, etc.). With current calculation methods, the national inventory would only report around 30% of the estimated overall abatement. This result demonstrates the need to focus on improving the French GHG inventory, a process already supported by projects under way (Mondferent, NO GAS2[15] projects, etc.).

In accordance with the study specifications, the measures and sub-measures proposed concern agricultural practices - as decided by the farmer - involving no major change to production systems or outputs. For a few measures liable to generate moderate yield reductions (No-till, for example), these were estimated and the corresponding cost was quantified. The measures and sub-measures envisaged are therefore compatible with the maintenance of efficient agriculture in terms of production. They concern a diverse range of stages and supply chains in the agricultural sector (nitrogen fertiliser application, tillage, animal nutrition, manure management, etc.). Measures liable to have a low level of social acceptability were eliminated (antibiotic use, for example). Among the sub-measures proposed, only the use of nitrate in animal nutrition to reduce CH_4 emissions could be controversial from this point of view. Likewise, measures still requiring further research or the acquisition of references, or concerning supply chains of limited scope, were not examined. The overall abatement calculated can therefore be considered to be a conservative estimate of the abatement potential of the agricultural sector.

A third of the abatement potential has a negative cost. This result is consistent with that found in similar studies conducted in other countries. This abatement potential with dual benefits - environmental and economic - concerns technical adjustments capable of simultaneously reducing GHG emissions and production costs due to better input management (nitrogen fertilisers, energy, etc.). The existence of this abatement potential with a negative cost raises the question of adoption obstacles (risk aversion, barrier to adoption generating non-measurable costs, etc.). Private transaction costs, calculated for some measures and related to the technical nature and complexity of their implementation, may partially explain the non-adoption of these measures. Most of this abatement potential with a negative cost is related to nitrogen management (nitrogen fertiliser application to crops and grassland, legumes, nitrogen content in the diet of livestock). The value of these measures concerning nitrogen management is further reinforced when induced emissions - linked, in particular, to the manufacture of synthetic nitrogen fertilisers - are taken into account, and when the other environmental and public health issues related to nitrogen management (nitrates, drinking water and aquatic ecosystem quality; ammonia and air quality) are considered. One problem is that a major proportion of this abatement potential involves technical levers for which a monitoring/verification system is difficult to implement (calculation of nitrogen balance with a credible yield target, dates and methods of nitrogen fertiliser application, adjustment of nitrogen contents in animal feed, etc.).

Another third of the expected overall abatement potential corresponds to sub-measures with a moderate cost (less than €25 per metric ton of CO_2e avoided). This category includes sub-measures requiring dedicated investments (Methanisation, for example) and/or modifying the cropping system slightly more (reducing tillage, agroforestry), potentially leading to moderate reductions in production outputs. This partially explains the positive cost calculated, but with input savings (fuel, for example) or economic outlets for additional products (electricity, wood). Here, estimation of the abatement potential is highly sensitive to the hypotheses relative to the potential applicability of the measures (surface area or manure volume concerned) and the cost depends greatly on the prices used in the calculations. An assessment excluding state subsidies increases the value of no-till systems and reduces that of methanisation. These measures also contribute to other agri-environmental objectives: production of renewable energy (Methanisation), reduction in erosion risk (No-till), landscape quality and biodiversity (Agroforestry). Reduced tillage may lead to an increase in the use of herbicides, but the technical option favoured (tillage one year in five) limits this risk. Implementation of a monitoring/verification system for these measures is possible.

The third part of the expected overall abatement potential has a higher cost (greater than €25 per metric ton of CO_2e avoided). This cost is related to specific investments (flares), input purchases (nitrification inhibitor, unsaturated fats or additives incorporated into the feed rations of ruminants) or dedicated labour time (cover crops, hedges), with no economic outlets for the additional products, and/or greater losses in production output (grass buffer strips reducing the cultivated area, for example). This group includes a measure that has already been the subject of a "domestic project" label (Fats sub-measure). Some of these measures nonetheless have a positive impact on other agricultural and environmental objectives (for example, effects of cover crops, grass buffer strips and hedges on biodiversity, the appearance of landscapes, erosion control, reduction of pollutant transfer to water). These measures contribute to multiple objectives and their value and cost cannot be assessed solely in terms of their effects on GHG emissions abatement. For some of them, the economic balance could be improved by finding economic outlets for products not quantified at present (production of grass buffer strips, for example). Most of these measures are traceable and verifiable.

A number of uncertainties - of varying origins and magnitudes depending on the measures concerned - emerge when estimating the abatement potential and cost of the measures and sub-measures examined. The levels of uncertainty concerning the unitary abatement potential are generally high given the marked variability in the processes and the difficulties encountered when measuring gas emissions. Efforts to acquire references must focus on measures for which the abatement potential is high but associated with significant levels of

[15] Project aimed at developing a "tier 2" method for calculation of N_2O emissions by agricultural land.

uncertainty, particularly concerning the unitary abatement potential. This is the case for no-till cropping systems, grasslands or agroforestry, for which little information is available in temperate environments. In particular, these efforts should make it possible to determine a complete GHG balance taking into account all the gases (both carbon storage and N_2O emissions for no-till cropping systems, for example).

The majority of the measures and sub-measures proposed are simultaneously compatible with the adaptation of the agricultural sector to climate change. The development of legumes, which are relatively sensitive to water shortages and periods of hot weather, could nevertheless be adversely affected by climate change. A reduction in rainfall could also limit the potential applicability of measures liable to generate competition for water to the detriment of the main crop, as is the case for cover crops or agroforestry.

A number of the major technical levers for emissions abatement in the agricultural sector that emerge from this study have also been highlighted in similar studies in other countries (nitrogen fertiliser application, no-till cropping systems, grassland management, for example). The approach of the French study favoured technical levers that are well documented, socially acceptable and already available, to the detriment of more exploratory levers. This characteristic suggests the need to update the study once additional information has been acquired concerning these levers.

The short-term study follow-up measures are as follows:

(i) the acquisition of the required additional references concerning technical levers with high potential but accompanied by significant uncertainties, such as agroforestry in temperate environments;

(ii) support for the improvement of inventory methods, so that they can take into account the effect of the measures proposed;

(iii) multicriteria assessment of measures contributing to several agricultural and environmental objectives (grass buffer strips, hedges, cover crops, no-till cropping systems, etc.) for which it would be simplistic to make assessments solely on the basis of GHG emissions abatement; consolidation of calculations on the basis of induced emissions in order to consider the consequences of the measures on the carbon balance of agricultural products using LCA methods;

(iv) identification of incentive measures liable to encourage the adoption of the measures presenting the best properties.

This study has revealed a significant agricultural sector emissions abatement potential by 2030, linked solely to technical levers, without affecting production systems, their location and production levels. This abatement potential has been demonstrated on the basis of just 10 major measures using a cautious approach, which probably means it has been under-estimated. The implementation of these measures should make it possible to reduce agricultural sector emissions in the coming years. Beyond the time period set for this study (2030), some of the measures proposed present an abatement potential that is reproducible year on year (Fertiliser application, Methanisation, Animal nutrition, for example). But, for others, the expected annual abatement will reach a ceiling, particularly for measures aimed at increased carbon storage in soil and biomass (No-till cropping systems, Cover crops, Agroforestry, etc.). To achieve more ambitious abatement objectives, it will be necessary to explore additional but complementary levers in the longer term - either technical (plant selection to improve nitrogen uptake efficiency, animal selection to reduce enteric methane production, etc.) or systemic, (re-combination of arable and livestock production, nutritional changes, etc.) - and construct scenarios. This study could be usefully supplemented by identification and evaluation of these other types of levers.

Study participants

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Isabelle Savini	editorial support, drafting of summary documents
Sophie Le Perchec	documentary support
Marion Barbier	logistics, accounting follow-up

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• Technical committee members

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** In bold: responsible for the analysis of a measure

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