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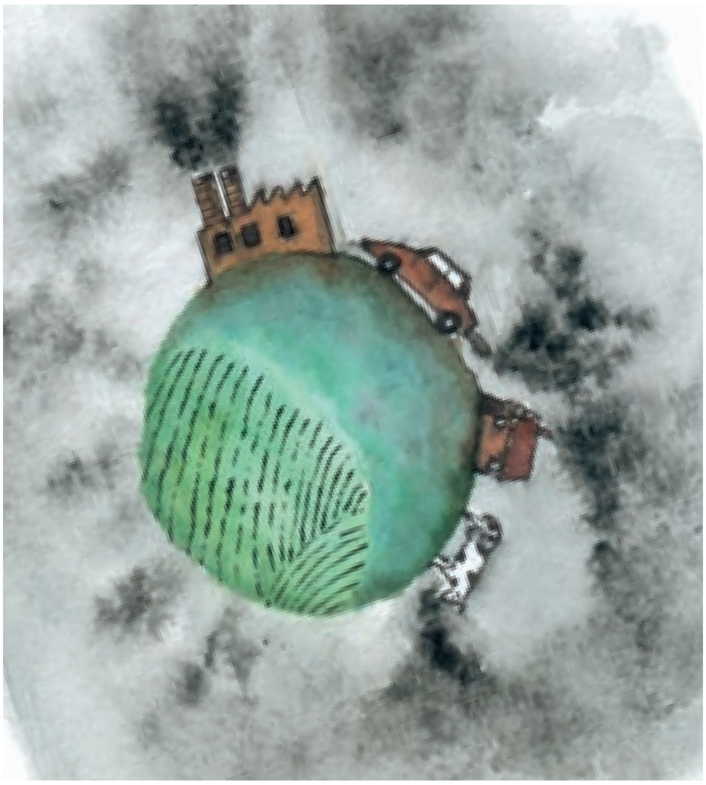

Mitigation of the greenhouse effect

Increasing carbon stocks in French agricultural soils?

D. Arrouays, J. Balesdent, J.C. Germon, P.A. Jayet, J.F. Soussana, P. Stengel (eds)

Scientific Assessment Unit for Expertise

Synthesis of an Assessment Report by the French
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FOREWORD

At the Earth Summit in Johannesburg, declarations by some States raised hopes that the Kyoto Protocol could be implemented in 2003. A reduction in the human induced greenhouse gas emissions is clearly the most sustainable policy to slow down the accumulation of these gases in the atmosphere, which is causing, according to a large scientific consensus, climate change. However, in the case of CO_2 emissions, possible alternatives consist in stocking for some time some additional organic carbon in the biomass and in the soil organic matter. Carbon stocks in the forest biomass (Article 3.3. of the Protocol) have already been the subject of international agreements, with strict quotas being imposed on different countries. Favouring a more or less long-term accumulation of organic matter in soils, through changes in land use and agricultural or forestry practices, is another alternative (Article 3.4.) which was accepted as a mode of application of the Kyoto Protocol. With respect to this alternative, there are no limitations as to the amounts accumulated or the land surface concerned, but no methods for verification have yet been defined.

Worldwide, soils contain about 1500 gigatons of organic carbon. A relatively small increase in these stocks could therefore play a significant role in limiting the net flux of greenhouse gases towards the atmosphere. Changes in land use and agricultural production practices could contribute to this, notably by increasing the magnitude and the duration of organic carbon storage in soils. The residence time of carbon in the soil organic matter is highly variable, as it varies with the rate of carbon mineralisation, through which organic carbon is finally returned to the atmosphere in the form of . It is therefore important to determine the potential offered by this pool, as a function of soils, their uses and associated practices. In order to apply the Kyoto Protocol, it is also necessary to know how and with what precision this pool could be measured, and which incentive policies could induce additional accumulations in soils.

The approach adopted by the French Ministry for Ecology and Sustainable Development (MEDD)

These challenges are not negligible for France in a European context, because of its large agricultural land and surface area. For this reason, the Ministry for Ecology and Sustainable Development requested an Assessment Report from INRA, which concerns the capacity for organic carbon accumulation in agricultural soils and its time-related dynamics.
This Expert Report should be read in the context of a strategy for soil management on a national basis, bringing together the principal actors in a Scientific Interest Group (Ministry for Ecology and Sustainable Development, Ministry for Agriculture, French Institute for the Environment, Agency for the Environment and energy resources, INRA) and the implementation of a soil quality monitoring network. At the European level, this report is in line with the recommendations of the recent Communication of the European Commission on soil protection.

The main questions for this assessment have been formulated by a Steering Committee, consisting of representatives from the main public bodies concerned and from INRA, and chaired by the Director for Economic Studies and Environmental Evaluation at the MEDD. These questions are as follows:

- *Can we, in France, through actions specifically targeting an increase in organic carbon accumulations in soils, contribute to reduce the greenhouse effect? The answer to this question is of direct interest to the French Interministerial Mission on the Greenhouse Effect, and France in general, so that agriculture can be taken into account in the national plan to combat the greenhouse effect.*

- *How could such actions meet the conditions of compliance with the Kyoto Protocol? It is necessary to propose solutions which will be technically feasible and economically viable.*

- *Which economic policy tools would be effective to promote the changes required? In this respect, it must be possible to integrate the tools in the Common Agricultural Policy.*

- *What are the needs in terms of research and references? What is required to further develop the research results and recommendations arising from MEDD pilot programmes concerning the sustainable management of soils and the impacts of climate change?*

Implementation of the project by INRA

This Assessment Report was drafted by an Expert Group consisting of researchers specialised in soil sciences, agronomy, bioclimatology and public economics applied to agriculture, from INRA and from other French and foreign organisations. INRA was designated for organising the project, which was entrusted to the Scientific Assessment Unit at the Environment and to the Forestry and Agriculture Scientific Directorate. They ensured compliance of the study with the methodologies of Assessment Reports, and with the requirements from the Steering Committee. Indeed, an Assessment Report, bringing together researchers from different areas, was necessary to consider a series of complex, scientific questions which are controversial. This report, through the assessment it has enabled and without omitting any debates and uncertainties, will provide an unquestionable aid for decision-makers.

This "Synthesis", more particularly drafted for Decision-Makers, was compiled by the Scientific Assessment Unit of INRA and was validated by the scientific experts. It forms a detailed summary of the report, with cross references to the chapters of the expertise which will provide readers with a more comprehensive information. As such, we hope it will provide all those interested in this important debate for the future of the planet with the ideas necessary for their thinking on national and European initiatives.

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INCREASING CARBON STOCKS IN FRENCH AGRICULTURAL SOILS?

The hypothesis of climate changes due to anthropogenic activities, induced by an increase in atmospheric greenhouse gas levels* [1] , is the subject of almost unanimous consensus in the international scientific community. This increase in greenhouse gas levels is due principally to CO_2 arising from the use of fossil fuels.

The actual increase in atmospheric CO_2 levels has proved to be less marked than was previously anticipated from CO_2 emission records and oceanic uptake, which has led to postulate the existence of a carbon "sink"* in continental ecosystems. Demonstration of this sink has made it possible to envisage its use and development to sequester carbon and thus slow down the current rise in the greenhouse effect.

1. CONTEXT AND OBJECTIVES OF THE ASSESSMENT REPORT

The Kyoto Protocol allows signatory countries listed in Annex I to subtract from their national greenhouse gas emissions any sequestration of greenhouse gases induced by "additional human activities". These activities principally target the uptake of carbon in biomass and the soil. They concern firstly forestry activities (Article 3.3. of the Protocol), and secondly agriculture and forestry management ("Land Use, Land Use Change and Forestry" [2], the subject of Article 3.4.). The amounts deductible under the terms of the "agriculture" section of Article 3.4. are not, in principle, limited; each country fixes the levels it undertakes to ensure, but their accounting is conditioned by the requirement to verify by an independent method the sequestration it claims.

France already emits low levels (per inhabitant) of CO_2, and will encounter problems in further reducing such emissions. Given the amount of land devoted to agriculture in France, the prospects opened by Article 3.4 may be of interest for the national policy of greenhouse gas mitigation.

➜ In this context, the Ministry for Ecology and Sustainable Development has asked INRA to carry out a scientific assessment study on the following theme: Can we, in France, through actions aimed specifically at increasing organic carbon stocks in agricultural soils, contribute to reduce the anthropogenic greenhouse effect?
It is necessary to examine the changes in the use of agricultural land and in farming practices which are covered in principle by the terms of Articles 3.3. and 3.4., their ability to actually increase carbon stocks under French pedoclimatic conditions, their possible application to the current technical and economic context of French agriculture and the means necessary to verify these stocks.

1.1. Current state of negotiations concerning the implementation of the Kyoto Protocol

Since the Kyoto Protocol (1997), negotiations have been continuing through the annual Conferences of the Parties in the UN Framework Convention on Climate Change. The negotiations are supported by scientific assessments and by special reports produced periodically by an international panel of experts, the IPCC (Intergovernmental Panel on Climate Change, or GIEC in French). The IPCC has published in 2000 a special report on Land Use Land Use Change and Forestry (LULUCF) and has also provided in 2001 revised guidelines for greenhouse gas inventories.

- Activities potentially eligible under the terms of Article 3.4.

In its LULUCF report, the IPCC has proposed a list of "additional anthropogenic activities" liable to increase carbon stocks, and potentially eligible under the conditions of Article 3.4. These include notably the management of cultivated land (organic fertilisation, tillage, incorporation of organic waste, crop rotations, optimisation of fertilisation, irrigation, etc.), the control of erosion, the management of set-aside lands and pastures, the restoration of wetlands or markedly degraded lands, etc.

- Accounting and verification rules

Under the terms of Articles 3.3. and 3.4., only "intentional" additional carbon stocks, i.e. resulting from voluntary actions (therefore excluding, for example, carbon accumulation linked to the spontaneous growth of trees on abandoned agricultural land) undertaken since 1990 (the reference year from which all targets concerning the reduction of emissions have been defined). This rule raises the problem of determining the baseline, the reference level under a business as usual scenario. Finally, carbon accounting is based on defined "commitment periods", the first of which is fixed in 2008-2012, with reference to the situation prevailing in 1990.

[1] **1.*** *denotes terms defined in the glossary to be found at the end of this documen*

[2] **2.** *Land Use, Land Use Change and Forestry (LULUCF)*

The accounting of deductible carbon sequestration being limited by the obligation to prove carbon accumulation, the conditions governing this verification are crucial. At present, some principles have been defined. They allow for verification on the one hand of the carbon sink enhancing effect of the activity, and on the other of the surface areas involved in the activity. They require double checks (using two independent methods) of the carbon accumulation claimed. However, the modes of application of these principles are still under debate; depending on the level of requirement retained, the means of implementing them and their cost may prove prohibitive.

1.2. Challenges for France and its current commitments

In the context of the Kyoto Protocol, which was ratified in May 2002 by European Union countries, France has undertaken to maintain its greenhouse gas emissions at their 1990 level. This objective of straightforward stabilisation, fixed because the emissions are already relatively low (due in part to the importance of French nuclear energy generating capacity) will nonetheless require efforts to compensate for increasing emissions from sectors such as transport.

For 2000, gross French emissions[3] of greenhouse gases were estimated at 148 million tons of carbon equivalent [4], and net emissions at 133 MTCE. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases contribute to 69, 13, 16 and 2 % of these net emissions, respectively. In 1990, net emissions reached 137.6 MTCE. The reduction recorded since that time corresponds to a reduction in non CO_2 greenhouse gas emissions, and mostly of N_2O from the industry sector.

- The role of agriculture

Agricultural and forestry activities are responsible for 16% of gross French greenhouse gas emissions, or nearly 24 MTCE. These two sectors also contribute to carbon storage at a rate estimated at 15 MtC per year.
Agricultural activities are the cause of:
- 67% of French emissions of N_2O (emissions from agricultural land and from animal wastes),
- 54% of French emissions of CH_4 (enteric fermentation in ruminants and animal wastes).

In contrast, direct agricultural emissions of CO_2 (fossil fuel consumption by agricultural machinery) only account for a small proportion of total French emissions.

➜ Soil carbon stocks in mainland France have been estimated (*cf. infra*) at approximately 3 billion tons. Therefore, French emissions, which are estimated at 148 million tons equivalent per year, are equivalent to approximately 4.9 % of the soil organic pool. An annual increase in these stocks of 0.2 % (6 Mt) would compensate for 4 % of gross annual greenhouse gas emissions, or about a quarter of the emissions from the agricultural and forestry sectors. These orders of magnitude justify attempts to quantify the effects of land use changes and agricultural practices on soil carbon stocks.

- Challenges and timing

The challenges are numerous:
- should France undertake additional agricultural activities complying with the conditions of Article 3.4. for the period 2008-2012? For the time being, only forestry management activities have been proposed with an emission reduction target of 2.6 MtC;
- the pursuit of the UNFCCC negotiations, in the context of annual CoP, to define in particular the methods required to implement Article 3.4. These questions require the opinions of experts, particularly at a European level[5] ; they are also being studied by a new IPCC panel;
- the implementation or reform of national or European policies, not targeting carbon specifically but likely to take it into account (European proposal for a Directive on Biofuels and Soils, etc.), and/or concerning practices favourable to carbon accumulation (CAP and national agricultural policy in France, etc.).

1.3. The Assessment Report

- Scope of the report

The issues to be dealt with :
- are limited to agricultural land: forestry land and canopy biomass are excluded. Concerning forests, the evaluation will only concern the average accumulations in soils which can be expected from the afforestation of agricultural land;
- are limited to land in mainland France[6] ;
- need to take account of the other effects of carbon sink-enhancing practices on the greenhouse effect,

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[3] *"Gross" emissions = not accounting for land use changes, sinks and forestry; these items are included in "net" emissions. The difference between these two figures is principally due to subtraction of the carbon sinks.*

[4] *To draw up greenhouse gas accounts, the contributions of each gas are expressed in terms of global warming potential* (GWP), using a common unit, the ton of carbon equivalent (TCE). The global warming potential of each greenhouse gas is calculated from its radiative forcing effect and from its residence time in the atmosphere.*

[5] *Cf. particularly the publication in March 2002 of an Expert Report requested by DG6 at the European Commission (Freibauer et al., 2002).*

[6] *The question of tropical soil will be considered in a special assessment report from the MEDD.*

and their related environmental impact, which may reinforce or, on the contrary, reduce or call into question the usefulness of these practices. However, these points will only be approached qualitatively: identification of factors and their positive or negative impact, reference to their order of magnitude when available.

- The knowledge mobilised and its processing

This study includes:
- a critical synthesis of scientific findings published on carbon accumulation, which constitutes the core of this project;
- an examination of the agronomic and economic feasibility of implementing measures to enhance carbon stocks, and a review of the tools which could be used in France to verify these stocks. This analysis makes it possible to go beyond the definition of "potential surface areas" of application of measurements, and to propose more realistic land areas taking account of prevailing constraints;
- an original study which proposes carbon accumulation simulations for the entire country, based on scenarios which adopt practices deemed to increase carbon uptake, and a simulation of the detection of changes in stocks using a land monitoring system.

- The different stages of the diagnosis

The initial question has been broken down into subsidiary questions which correspond to the different stages of the diagnosis:
- an estimate of the additional carbon storage induced by different practices per unit of surface area (which enables an initial screening of the activities envisaged in Article 3.4),
- accounting of the other consequences of these practices on the greenhouse effect (emission of other greenhouse gases, economies in fossil fuels, etc.),
- accounting of other agronomic and environmental consequences which might reinforce or limit the usefulness of carbon sink-enhancing activities,
- an examination of agronomic constraints related to the behaviour of farming systems likely to restrict the extension of these activities, and an analysis of possible conditions for lifting these constraints,
- an evaluation of potential carbon storage in mainland France, according to several scenarios based on different carbon accumulating practices,
- an examination of the rules necessary to verify carbon stocks and an evaluation of existing verification methods,
- a review of economic and political tools which could be used as incentives for additional carbon storage practices,
- an overview.

2. CARBON STOCKS AND CARBON SEQUESTRATION IN THE SOIL: MECHANISMS AND METHODS FOR EVALUATION

2.1. The source of soil carbon and means to increase its accumulation

- The carbon cycle in terrestrial ecosystems

Photosynthesis is almost the sole pathway for the biological uptake of atmospheric CO_2 in these ecosystems. The organic matter (OM) thus synthesised is always ultimately degraded at one level or another of the trophic networks: by respiration (with the release of CO2) or, under anaerobic conditions, by fermentation (with the release of CH4). This OM can also be destroyed by combustion, which also gives rise to CO_2.

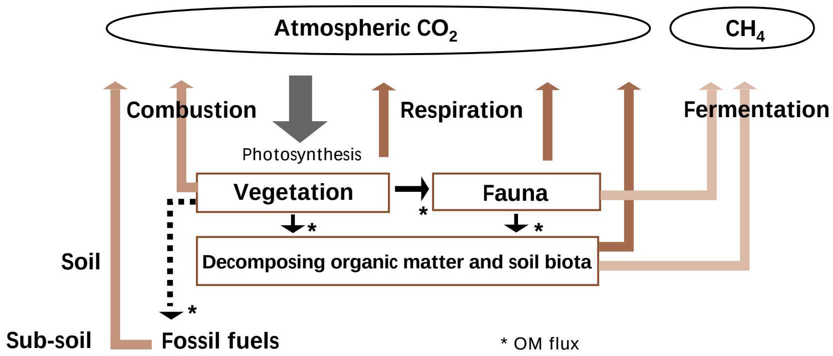


Figure 1. The carbon cycle.

At a planetary level, carbon stocks reach 750 Gt in the atmosphere, 650 Gt in vegetation and 1500 Gt in the soil. Average gross annual exchanges between the continental biosphere and the atmosphere reach 120 GtC/year.

- Carbon dynamics in the soil

Carbon can be accumulated in the soil, mainly in an organic form. This organic matter arises from plant parts (leaves, roots, etc.), dead organisms, animal waste and also rhizodeposition (deposition of organic compounds excreted by roots in the soil), and includes microbial biomass.

"Dead" OM undergoes a series of biotransformations, including decomposition and finally mineralisation by micro-organisms, with the release of CO_2. The rate of these phenomena depends on the composition of the OM and local physicochemical conditions (humidity, temperature, oxygen, etc.); it is slowed when OM is associated with mineral particles (particularly clay) which provide physical "protection" for this OM against the activity of micro-organisms.

➜ There is (almost) no definitive storage of carbon in the soil, because in the long term, any OM is mineralised. The residence times for organic carbon in the soil, which average some tens of years, can range from a few hours to several millennia. The evolution of carbon stocks is determined by the balance between the input of organic matter and the output of CO_2.

- Technical means of increasing the carbon pool in agricultural land

The agricultural activities likely to accumulate carbon are those which allow:

1/ an increase in the "input" of organic matter:
- by increasing primary production, which generally elevates the OM content in the soil;
- by increasing restitution to the soil of crop residues and animal waste (manure, etc.);
- by importing non-agricultural OM (spreading of organic waste of industrial or urban origin).

2/ a delay in "output" due to mineralisation:
- by slowing decomposition and then mineralisation through changes to the composition of OM, and also through land uses and agricultural practices which can modify physicochemical conditions and improve the physical "protection" of OM;
- by preferring "sustainable" uses for harvested OM (this point mainly concerns wood).

➜ Some land uses or agricultural practices affect several of these processes. Thus maximum additional accumulations are achieved by changing from an annual crop to perennial vegetation, which cumulates several effects: carbon inputs which may sometimes be higher (from above-ground and below-ground plant parts); OM is kept physically protected in the absence of tillage and bare soil.

2.2. Variations in soil carbon levels and problems in stock evaluation

- Problems encountered in estimating carbon stocks

Stock estimates are always based on point measurements of soil carbon contents, which are then converted into a pool (change from a content with reference to a soil mass to a pool with reference to a volume using bulk density); mean stock values are then extrapolated to surface areas considered as homogeneous. Such estimates come up against two major obstacles.

The broad variability of stocks

There are considerable temporal and geographical variations in soil carbon stocks, as well as a marked but variable vertical gradient (higher carbon levels on the surface, which decline with depth). Factors which may affect carbon stocks are numerous and their interactions complex.

In France, soil type and land use appear to be the principal controlling factors governing stock levels, but the dispersion of these values remains considerable, even within classes defined by crossing these two criteria. This marked residual variability is indicative of the importance of other parameters which are not taken into account, and also of the fact that carbon stocks measured at time t under a given land use does not often correspond to "steady state" stocks and reflects in part the previous uses of the site (cf. § 2.3).

The scarceness of the data available

The data available are too few in number (insufficient sampling in the context of the existing variations), not always reliable and complete (no measurement of bulk density, etc.) and not often comparable between each other (differences in analytical techniques, soil depth taken into account, etc.). The risks of errors and inappropriate extrapolations are therefore high.

➜ It is even difficult to obtain accurate estimates on average stocks; indeed, the world-wide estimates published vary by a considerable percentage. However, by taking some methodological precautions, it is nevertheless possible to obtain stock estimates, but only the orders of magnitude should be retained in this respect.

➜ In contrast, it is difficult to demonstrate variations in stocks. The relative amplitude of the changes is generally low and the evolution slow, and often masked by spatial and seasonal variations. Best estimates are obtained from long-term experiments.

● Carbon stock estimates in French soil

A review of around 19,000 references available in French databases has made it possible to produce an estimate of stocks by soil type and land-use class, then of national stocks and their regional distribution. All the data refer to the upper 30 cm of soils. This layer is supposed to account for 80 to 90% of the potential stock variations to be observed over decades.

Carbon stocks according to land use and soil type

Average stocks according to land use range from 30 to 90 tC/hectare, and can be broken down into 3 groups:

- land under annual crops and perennial crops with bare soil, where stocks are lower than 45 tC/ha. Vineyards and orchards and crops with a very low organic return have the lowest stocks: approximately 32 tC/ha. Arable land is also characterised by relatively low stocks: 43 tC/ha on average;
- land under permanent grassland and forests (excluding litter) exhibits average stocks of nearly 70 tC/ha;
- land under high-altitude pastures and in wetlands, where stocks are higher than 90 tC/ha (due to low temperatures and the effect of anoxia on carbon mineralisation, respectively).

➜ The most marked effect in terms of carbon accumulation is obtained by a change from the first (arable) to the second group. Grasslands and forests exhibit very similar soil carbon stock potentials.

Average carbon stocks **by soil type** range from 40 tC/ha (sandy or skeletal soils) to 100 tC/ha (clay or hydromorphic soils). A high clay content is the principal factor correlated with high soil carbon levels; however, high contents of calcareous (rendzinas) or aluminium (podzols) also make it possible to attain medium stock levels in low-clay soils.

Carbon stocks in France

Based on these mean carbon stock values by soil type and land use, and overlaying soil and land use maps, it is possible to compile a map of carbon stocks per hectare and then to calculate an estimate of global carbon stocks in French land.

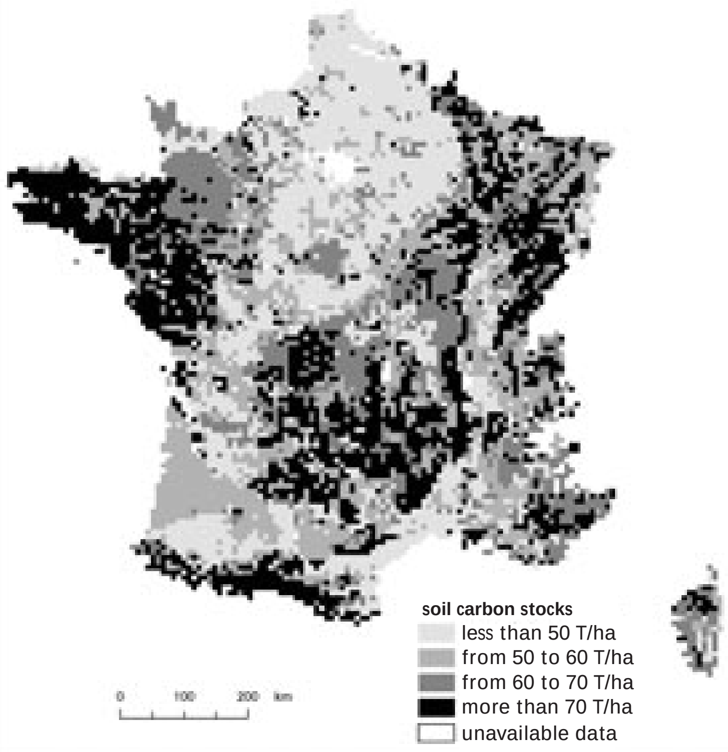


Figure 2. Geographical distribution of soil organic carbon stocks in France (0-30 cm).

We can see: the smallest stocks (<40 tC/ha) in wine-producing regions, with a hot climate and thin soil layer, and also in a few areas of highly intensive cultivation; small stocks (40-50 tC/ha) are found in the major plains of intensive cropping and in more or less degraded silt soils; average stocks (50-70 tC/ha) are found in the major forestry and/or pasture regions, and the highest levels are found where extreme climatic (mountains) and/or pedological (marshes) conditions prevail.

➜ These regional disparities indicate differences in both land use and pedo-climatic conditions. Carbon stock potentials vary considerably from region to region.

Estimated global stocks reach 3.1 Billion tons of carbon for the whole of mainland France, excluding overseas territories and dominions, for a soil depth of 0 – 30 cm.

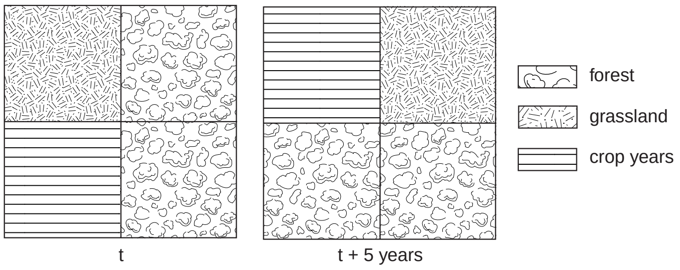
2.3. Kinetics of the accumulation and release of soil carbon

The kinetics of carbon accumulation following change in land use or practices are:
- non-linear: they are more rapid during the first years after adopting a practice which enhances accumulation. This phase does not usually exceed a few decades. If practices remain constant, the stocks tend to remain at a level corresponding to the establishment of a new equilibrium (where the input and mineralisation of OM compensate for each other).
- slower than those of carbon release. For example, over a period of twenty years, the accumulation arising from a conversion from arable → forestry use is half that of the release induced by conversion from forestry to arable use.

➜ These characteristics have several consequences:
- there is a risk of overestimating stocks by extrapolating mean annual fluxes over periods which are too long;
- soil stocks do not represent a sustainable, long-term solution to reducing atmospheric CO2 levels. After a few decades, accumulation no longer increases, but stock conservation requires maintenance of the practices which enabled its accumulation;
- the abandon or temporary interruption of stock-enhancing practices usually results in rapid release. To be effective, adopting a particular practice must be accompanied by an undertaking concerning its long-term pursuit. If interruptions prove necessary, the stocks claimed must be revised downwards;
- annual pool fluxes are not independent of the history of the plot. It is therefore not possible to evaluate carbon stocks which have accrued between two dates based solely on measuring the surface area concerned by changes in use or activities occurring over that period. It is necessary to know the land use change matrices.

Figure 3.

The proportions of different land uses do not vary between the two dates, but three plots have seen a change to their carbon accumulation/release equilibrium. In view of the asymmetry between accumulation and release, the overall result is a carbon loss.



- Knowledge and modelling of carbon transformation processes in the soil

Organic matter which arrives in the soil undergoes successive biotransformations, so that organic carbon may be found in different forms with different physicochemical properties and residence times.
No single, global model exists today which can integrate all carbon transformation mechanisms and factors, allowing a prediction of the course of carbon stock evolutions. The different models which have been proposed each correspond to specific conditions of application or particular objectives.

➜ At present, we have limited ourselves to models which are somewhat rougher but more robust than complex models, and which do not require too many input variables. This is the case of the Hénin-Dupuis model which has a single carbon compartment and two coefficients (one corresponding to the rate of conversion into humus of the OM added to the soil and the other to the rate of mineralisation of this humus). This model also has the advantage of being widely documented in France.

➜ The Expert Group has proposed a single, formal framework derived from this model to integrate the references available and describe the accumulation of carbon, while avoiding the biases referred to above.

3. CRITERIA AND EVALUATION METHODS CONCERNING AGRICULTURAL PRACTICES LIKELY TO INCREASE SOIL CARBON STOCKS

The practices eligible under the terms of Articles 3.3. and 3.4. need to be evaluated with respect to their carbon accumulation potential and also their related impact which may reduce or even cancel out their positive effect or, on the contrary, reinforce the usefulness of some activities.

3.1. Evaluation of carbon accumulation potential and its kinetics

The formal framework retained in the Expert Report to assess the carbon accumulation/release occurring after practice B has been adopted in place of the initial practice A (supposed to have attained its stock equilibrium) is an exponential function. Its parameters are: the difference Δ between carbon stocks at the steady state for practices A and B, and a constant rate k of accumulation/release. It is always possible to subtract from the stock values thus calculated a mean annual flux for a given period, for example, the first 20 years during which a new practice is applied. It is these mean flux values which are given in the present document.

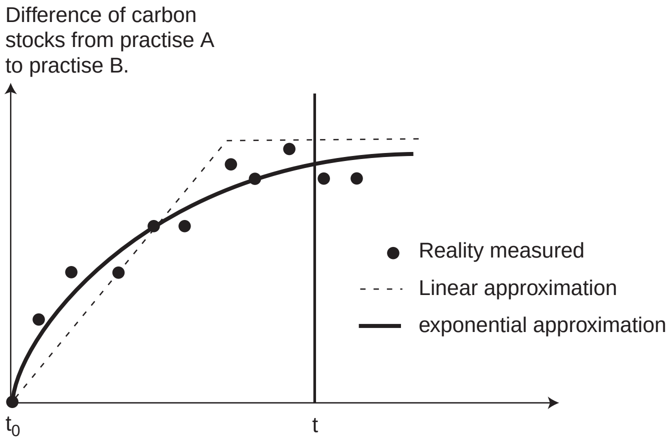


Figure 4. Two modes can be used to approximate carbon stock kinetics in the case of practice B replacing a different practice A.
The IPCC uses the bounded linear approximation.

An exponential approximation defined by the equation $Ct = \Delta\ (1 - e^{-kt})$*, is retained here. The curve obtained, which complies better with the kinetics observed than a line, presents an asymptote which avoids an overestimation of the stocks due to adding mean annual fluxes over a too long period.*

For each change in land use or practice, the two parameters have been estimated from the references available, priority being given to data gathered under pedoclimatic and agricultural conditions similar to those prevailing in France, and in the context of long-term agronomic experiments. It should be noted that in other reports the great majority of bibliographical references are American.

3.2. Accounting for other climatic effects of practices enhancing soil carbon stocks

- Emissions of other greenhouse gases

90% of total CH_4 of agricultural origin is produced by ruminants (enteric fermentation in the rumen); these emissions are not covered by this Assessment Report, but need to be included in any reasoning concerning breeding or livestock husbandry systems likely to optimise the greenhouse gas budget.
With the exception of rice paddies (negligible in France) and wetlands, land contributes little to CH_4 emissions, and very likely acts as a sink (due to the presence of CH4 consuming bacteria).

In contrast, N_2O emissions of agricultural origin are largely attributable to the land. These emissions are not evaluated in terms of surface area but by emission factor (percentage of nitrogen arising from fertilisers). According to the emission standards retained by the IPCC, direct annual emissions of agricultural N_2O may reach 117,000 tonnes for mainland France which, in view of the high global warming potential of this gas, is equivalent to carbon release of 9.4 MtC/year.

➜ The greenhouse gas budget is not always known with precision. We expect that some practices favourable to carbon accumulation may in fact exhibit a very weak result in terms of greenhouse effect reduction, because of increased emissions of non CO_2 greenhouse gases.

- Reductions in fossil fuel CO_2 emissions

By reducing the agricultural consumption of fossil fuels

If we take the example of non-leguminous annual crops under standard management, fossil energy consumption reaches, for example, 20,000 MJ/ha, which is equivalent to the carbon release of 0.40 tC/ha/year. For such crops, 40 to 60% of fossil fuel consumption corresponds to inorganic nitrogen fertilisers (the synthesis of which requires considerable energy), which can be saved by using N2-fixing legumes. Furthermore, some practices which accumulate carbon may also save more fossil energy, e.g. by reducing energy use by agricultural machinery.

By substituting green fuels for fossil fuels

The use of carbon from plants to produce energy enables economies in the emission of fossil fuel CO_2. This approach covers both the production of crops for green energy (oil seed rape to produce a methyl ester to be mixed with diesel, wheat or sugar beet to obtain bio-ethanol to be mixed with petrol after refining), and energy valorisation of crop residues (burning of straw). The greenhouse gas budget for these options should be compared with their effects on soil carbon stocks.

- Modifications to energy exchanges on the land surface

Land use changes may have effects on the climate system because of changes in surface energy fluxes: the relative proportion of reflected solar energy and that absorbed by the ground, heat emitted by the ground dissipated by evapotranspiration/heating of the air. This question falls outside the application of the Kyoto Protocol, but it must be taken into account if we are seeking to refine the radiative budgets of land areas, and is indeed the subject of scientific debate.

The effect of land use on the climate is well known and quantified at a local level. This impact on local climate (notably temperature) may compensate for climate warming or, on the contrary, enhance it. The consequences on the global climate lead to many difficulties in assessment and comparison with the effects of carbon accumulation. Changes to the use of large areas of land may have effects on the absorption of solar energy by the land and thus may reduce or even cancel out the expected effects of carbon accumulation on the greenhouse effect.

3.3. Agronomic and environmental impact of practices accumulating carbon

From an agronomic point of view, the effects of increasing OM are mainly positive: an improvement in the structural stability of soils, in their levels of nutrients and water reserves. However, these effects are difficult or even impossible to quantify.

A large number of "stock-enhancing" practices are accompanied by related environmental benefits: reduction in erosion and the pollution of underground and surface water, maintenance of biodiversity and/or gains regarding the consumption of fossil energy. However, some negative effects are possible: the cessation of tillage requires an increase in the use of pesticides, and major afforestation can result in the closure of landscapes, etc.

➜ The frequently proposed "win-win" hypothesis, according to which strategies aimed at increasing carbon accumulation will always bring other environmental benefits, needs to be verified on a case-by-case basis, and with reference to other environmental objectives which may be assigned to a region.

3.4. Technical and economic constraints on adopting land uses and practices which accumulate carbon

It is necessary to identify the technical and economic constraints which might oppose the adoption of practices which enhance accumulation (agronomic problems, cost of equipment, additional workload, evolution of markets, the ideas governing current agricultural grant schemes, etc.). This phase of the diagnosis provides an opportunity to envisage the technical assistance (consulting, etc.) and/or economic incentives which might facilitate the adoption and maintenance of these practices.

In addition, taking account of these constraints, of "spontaneous" developments in land use and agricultural practices, and of concrete opportunities to verify them serves to define the hypotheses which form the basis of stock simulations at a national level.

➜ There remain many gaps in our knowledge, resulting in uncertainties as to any quantifications or even the direction any expected developments will take. It is therefore difficult to draw up these accounts.

4. EVALUATION OF CHANGES TO LAND USE OR AGRICULTURAL PRACTICES LIKELY TO INCREASE SOIL CARBON STOCKS

A preliminary selection has been made amongst activities which might be eligible under the terms of Articles 3.3. and 3.4. regarding the "accumulation potential" criterion, and with respect to other massive effects on greenhouse gas emissions or the environment. The options retained have then been examined more closely with respect to their conditions of implementation. These points are summarised in Table 1.

4.1. Afforestation of agricultural land

Afforestation of arable land

Analysis of the data in the literature has enabled an evaluation of the mean annual soil carbon storage induced by the afforestation of arable land at 0.45+0.25 tC/ha/year, based on a 20-year scenario. Conversion the other way (cultivation of woodland) generates a considerable release of carbon which is twice as rapid as the accumulation which results from afforestation (Figure 5).

Such afforestation is interesting in terms of accumulation, but since the poorest soils have already become forests, the "reserves" of land are probably limited, unless land currently in permanent set-aside is made available for afforestation.

Afforestation of grassland areas

Supplementary accumulation in soil would be minor due to similar stocks in grassland an woodland; a moderate release may even be observed under certain pedoclimatic conditions.

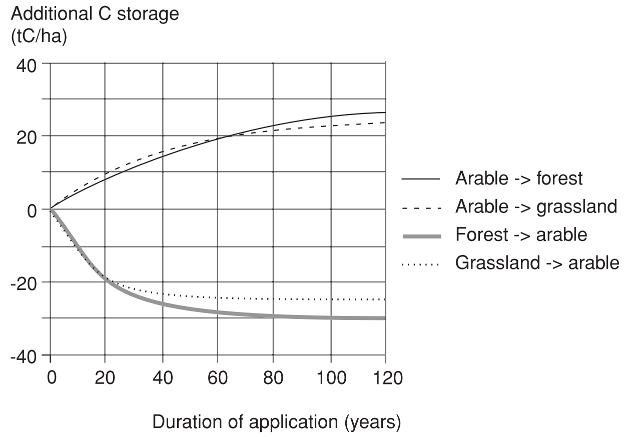


Figure 5. Evolutions in soil carbon stocks associated with practices which enhance extremes of accumulation (0.5 tC/ha/year for the first 20 years) or release (1 tC/ha/year).

These are modal values for mainland France; the 95% confidence interval of these values is about ±40%.

The afforestation of agricultural land also enables an accumulation of C in the woody biomass (not included in the context of this report) and has other positive effects on the greenhouse gas budget: saving of inputs (nitrogen fertilisers) and traction energy, etc.

To be included under the Kyoto terms, such changes from arable land to forestry must result from a voluntary human action: the spontaneous afforestation of abandoned land can not therefore be taken into account unless it is accompanied by management of this extension. It should be noted that the restoration of forests damaged in France by the storms in December 1999 has probably reduced the human and material means available at present to implement new afforestation operations.

Planting of hedgerows

The creation of hedgerows, narrow, wooded bands, does induce an increase in carbon stocks, but this varies considerably as a function of the characteristics of the hedgerow (size, height, location in landscape, etc.). The order of magnitude may be 0.1 tC/ha/year for 100 linear metres of hedgerow per hectare. On a slope, when hedgerows run parallel with the contours, they retain eroded soil above them, thus preventing the export of OM from this soil.

Previously removed in mass during land consolidations, hedgerows are now being reconsidered for their environmental value: they control run-off and erosion, have positive effects on the biodiversity and development of wildlife in integrated protection systems, they protect cattle at pasture and are of value to the landscape, etc. However, the costs of planting and maintaining hedgerows have limited their development.

4.2. Changes to land cultivation practices

We only consider here land under annual crops, and we do not include fodder crops nor conversion to grassland (which are the subject of § 4.3). The envisaged changes to practices do not, in principle, call into question these production systems; they may require a more or less extensive review of management sequences and hence adjustments to cropping systems.

- Level of cropping intensification

Practices aimed at increasing primary production by intensification (increased fertilisation or irrigation) are not retained as enabling an increase in carbon stocks, given the slight gains possible in systems which are already highly intensive, and the negative side effects of such a strategy on the greenhouse gas budget (emission of N_2O, etc.) and on the environment. Nor have genetic improvements, which increase the amounts harvested but not the quantities returned to the soil, been retained.

In contrast, some degree of "de-intensification" in European intensive agricultural systems does not penalise carbon storage and exhibits a more favourable greenhouse gas budget; reductions in nitrogen fertiliser lead to lower emissions of N_2O and energy consumption, and fewer machine runs (fewer plant health procedures) allow further savings in fossil CO_2.

- Choice of crops

Crops ensuring a higher organic return

The carbon accumulation induced by crop residues returned to the soil differ as a function of crop production type: for example, cereal straws provide more carbon (0.15 tC/ha/year for 7 tons of straw) than the residues of potatoes or sugar beet (crops inducing a release of carbon). But a further increase in the share of cereal crops in a rotation plan is contrary to developments towards more diversified cropping plans aimed at limiting pest risks (and which are indeed encouraged by "rotation premiums").

Energy crops

These enable savings in fossil carbon emissions which exceed sequestration through an accumulation of carbon in the soil. Furthermore, they may constitute a sustainable solution, the efficacy of which is not limited over time, unlike soil carbon stocks.
Low-fertiliser crop management (moderate fertilisation, reduced tillage) should make it possible to optimise the greenhouse gas and environmental budgets of these energy crops. However, it is not sure that this option ensures the best economic profitability under current conditions.
At present, the most advanced production of biofuels in France is that of diester using high levels of inputs; however, it represents only 300,000 hectares of oil seed rape. The European Biofuels Development Project should nevertheless ensure further development of this activity.

- Management of crop residues and exogenous inputs

Management of crop residues

Most crop residues are already returned to the soil – the burning of straw in fields is now quite uncommon. The possibilities of enhancing carbon stocks in this respect are therefore almost nonexistent.
The energy valorisation of these residues may be of more interest in terms of the CO_2 budget than the accumulations induced by their return to the soil. For 7 tons of straw, the soil carbon accumulation is estimated at 0.15 tC/ha/year, while combustion would allow economies of 2.4 tC, or a gain of 2.25 tC/ha/year. However, development of this energy use raises problems of collection and equipment, and would cause a reduction in OM which could be harmful to soils receiving no other organic input.

Management of farm animal wastes

Farm animal wastes represent a major carbon pool (approximately 25 MtC/year), but they are already spread on agricultural land. Proposals to "improve" their management, based on spreading them on other soils with low OM levels, have been put forward by some authors. This option would suppose that this OM would be stabilised, and could result in additional costs in terms of energy for transportation. According to our present scientific knowledge, management of these wastes therefore represents a nil potential for supplementary accumulation.

Import of exogenous, non-agricultural organic matter

The exogenous OM which could be utilised consists of organic wastes from the agrofood industry or towns (sludge from waste water treatment plants, household compost and green wastes). The possible gains are in fact limited, because, in France, most of these wastes are presentlly dumped or incinerated with production of energy; the incorporation in the soil of the material that is currently incinerated without production of energy represents a potential national accumulation of ca. 0.15 MtC/year. In terms of greenhouse gases, their energy valorisation would be of more value. Nevertheless, spreading on agricultural land constitutes a local recycling pathway for this waste.

Spreading of these products may raise problems (which can be solved) in terms of controlling nitrogen fertilisation (variable N content of inputs, mineralisation difficult to predict, etc.). It also comes up against the reticence of farmers (and landowners) who fear that the health hazards (e.g. heavy metal load) and/or the poor image linked to such spreading would then restrict the crops which could be grown on this land (for example, regulations limiting the spreading of sludge on land used for vegetable crops).

➜ With the exception of their use to produce energy, the management of crop residues, farm waste and urban waste offer a low potential for supplementing CO_2 stocks.

- Management of unproductive land

The planting of intermediate crops (as intercrops or on set-aside land) or catch crops is retained, as they increase annual primary production without the use of supplementary inputs, and imply the total restitution of OM because plant products are not exported.

Introduction of green manure into intercropping systems

The use of green manure (non harvested production) during sufficiently long intercrop periods (between a summer harvest and spring sowing) represents an interesting solution in terms of carbon accumulation: 0.15 tC/ha/year. Its introduction in present-day cash crop systems does not involve any insurmountable difficulties. The main problem is control of the nitrogen input for the next crop; reconstituting soil water reserves and the labour calendar must also be considered. We need to have a clearer idea of the long-term effects of systematically introducing green manure into current cropping systems (mineralisation and management of nitrogen, parasitism, etc.).

The use of green manure, already encouraged in the context of intermediate nitrogen fixing crops and protecting soils during the winter, is already quite widely developed. The use of cropping models would enable optimisation of the dates of establishment and destruction of these plant canopies, and control of their effects on the carbon or nitrogen cycle and on the water balance.

Sowing grass under perennial crops

The sowing of permanent grass between rows of vines or fruit trees enables an increase in carbon accumulation nearly equivalent to that induced by converting arable land into permanent grassland, i.e. 0.4 tC/ha/year.

This practice, which is also of value to improving soil bearing capacity, does not raise any particular problems if the water supply is not too deficient. Grass in orchards (which is obligatory in integrated fruit production systems) is indeed quite common in regions where water is not too restricted. Sowing grass between vines in regions with a dryer climate, is more problematical.
An extension to this practice would require the development of research on the effects of competition for water and nitrogen between the cover plants and the crop, on its possible impact on wine quality and on the control of pests that a maintained grass cover would encourage.

Management of set-aside land

Bare set-aside land, which induces a marked release of carbon (0.6 ±0.2 tC/ha/year) must be proscribed; indeed, it was only authorized by the CAP during two years (1993 to 1995).
The current level of bare set-aside in France is 0.4 Mha. Other set-aside land is usually covered by unharvested grassland. Short-term set-aside land is particularly well suited to energy crops. Long-term set-aside land (fixed) could be managed as perennial grass cover (equivalent in terms of carbon accumulation to a permanent grassland), sites being chosen as a function of related environmental objectives (anti-erosion grassy strips or river banks) or be authorised for afforestation.

Extensions of these three types of plant cover realized since 1990 could be claimed under the conditions of Article 3.4.

- Suppression of tillage

No till induces an increase in soil carbon levels. Simplified cropping techniques (SCT), defined by no-tillage, cover a broad range of practices, ranging from direct drilling to more or less deep ploughing (but without turning the soil). Direct drilling and minimal soil cultivation would have comparable effects: the increase in carbon accumulation is evaluated at 0.20 ±0.13 tC/ha/year.

No-tillage is a practice which spreads "spontaneously" because of the economies of labour it produces. Its generalisation may be limited by the cost of special equipment (drills, machines which limit the packing of soil) and by the agronomic problems it may generate or aggravate (compacting of soil, proliferation of weeds or pests, etc.). These difficulties lead farmers to alternate tillage and direct drilling, and to adopt intermediate simplified working practices on land where a lack of any cultivation would be detrimental. Farmers lack references to make such technical choices, and studies should be performed on the consequences of the various options available under different environmental conditions.

No-tillage constitutes a means of combating erosion. It also has certain negative effects: it generally induces an increase in the use of pesticides to destroy the weeds and pests which are usually controlled by tillage (no-tillage is therefore practically impossible for organic farming); some references in the literature have shown an increase in N_2O emissions. It would therefore be necessary to evaluate more precisely the impact on carbon accumulation and N_2O emissions of other conservation practices, halfway between tillage and no till. It should also be noticed that carbon stocks accumulated with no-till will be partly released by a single tillage event.

4.3. Changes to fodder management systems

- Conversion of arable land into permanent grassland

The carbon fluxes induced each year by converting arable land into permanent grassland are estimated at 0.50 ±0.25 tC/ha/year over a 20-year period. The variability in these results is due principally to the diversity of climatic conditions. Carbon accumulation is half as slow as the carbon release which occurs after a grassland is ploughed (Figure 5). Conversion into a managed grassland (high biomass level) accumulates more carbon than the spontaneous development of temporary grass on abandoned arable land.

The conversion into permanent grasslands of temporary or artificial, multiannual pastures, where carbon stocks are already intermediate between that of arable land and permanent grassland, induces a more limited increase in accumulation.

The environmental benefits of permanent grasslands are numerous: increased biodiversity, reduction in nitrate leaching to the water table, etc.

Farms raising domestic herbivores occupy two-thirds of farmland in France, and 60% of all professional farms raise some herbivores. However, grasslands (land under permanent grass), which in mainland France occupy about one third of the land, have markedly declined since 1970, to the benefit of arable land (including fodder crops such as maize silage), fallow land and heathland.

Restoration over 20 years of half the amount of land under permanent grass lost since the 1970s would lead to a mean annual increase of 90,000 hectares in the surface of grasslands, and could be accompanied by a marked increase in soil carbon stocks. However, this would imply major changes to breeding systems and grassland management sequences. In addition, the consequences on the emissions of other greenhouse gases (CH_4 and N_2O) are still unknown.

- Grassland management sequences [7]

Management of permanent grasslands

Increased fertilisation induces not only a rise in production but also an acceleration in mineralisation and enhanced decomposition of OM. Optimisation of carbon stocks requires a compromise between these different phenomena; it seems to have been attained for rich grasslands. Carbon stock-enhancing practices are therefore those which involve a certain reduction in the intensification of highly fertilised grasslands and a moderate intensification of poor grasslands. However, mountain pastures and wetlands should be excluded from the latter practice, because they are naturally endowed with high carbon levels which intensification could reduce by 1 tC/ha/year.

Under the conditions prevailing in Europe, grazing often increases carbon accumulation when compared with cutting. In general, the conversion of permanent grasslands into temporary grasslands results in carbon release.

7. *The effects of grassland management on carbon accumulation are rarely quantified; for example, no figures are given in the European Expert Report published in March, 2002*

Management of temporary grasslands

Temporary, multiannual grasslands exhibit an intermediate potential for carbon accumulation, between those of permanent grasslands and arable land. This potential increases in line with prolonging the lifespan of covers, i.e. less frequent ploughing.
The introduction of legumes improves annual productivity while reducing inputs of nitrogen fertilisers; it appears that the highest carbon levels are obtained with mixtures of grasses and pasture legumes.

The management of grasslands and fodder crops is always designed as a function of herd feed requirements and thus the raising system. For this reason, the Expert Report proposes a classification of fodder systems, and describes the possibilities for their development.

● Changes to fodder systems

Domestic herbivore breeding is still generally based on grassland use, since herbivores occupy more than 80% of all land put down to fodder crops (as opposed to 15% for maize silage). However, the share of grass differs considerably as a function of production system: it reaches nearly 95% in cattle farms which breed for meat production, but is much smaller in, for example, the 49,000 dairy farms which produce half of all French milk and 20% of French meat using much more intensive production systems (with 41% of maize silage and a stocking rate of 1.7 Livestock Unit/ha).

Extensification of intensive herbivore raising systems

The extensification of intensive herbivore raising systems constitutes an interesting option to enhance soil carbon accumulation by using more grasslands (conversion of annual fodder or cereal crops into temporary grasslands, conversion of temporary grasslands into permanent grasslands, etc.). This extensification could also be accompanied by a reduction in CH_4 emissions per hectare (because of a lower stocking rate) and in N_2O emissions (limited nitrogen inputs). In the latter case, however, it is necessary to take account of the emission coefficient associated with symbiotic nitrogen fixation by leguminous crops, which current evaluations place at the same level as nitrogen fertilisers.
Such a development can be envisaged, as shown by the example of breeders in Western France who have radically changed their herd feeding system (abandoning maize silage, limiting concentrates and ensuring a maximum use of grazing) and simplified their production system. This extensification results in a considerable reduction in costs and a moderate fall in productivity (1000 to 1500 litres less milk per cow), which may lead to improved revenues and shorter working times.

Increasing the use of grass in raising systems

The "extensive grazing system subsidy", associated with policies targeting quality (production of wines, cheeses, labelled meats, etc.) has slowed the intensification of fodder systems and favoured the maintenance of permanent grasslands on extensive farms in medium-altitude grassland regions. To favour the development of grasslands, several options can be proposed to optimise the use of grass on these farms: an increase in the length of the grazing season, the use of deferred grazing, the production of grass at a lower cost by using grass-legume mixtures or permanent grassland and an improvement in the valorisation of organic fertilisers.

➜ To quantify potential additional carbon storage at a national level, a global assessment of the "grasslands-livestock farming" sector is necessary. This should in particular include emissions of CH_4 by ruminants, which make an important contribution to agricultural emissions of greenhouse gases, and emissions of N_2O associated with grazing and with symbiotic nitrogen fixation. This assessment will require specific research efforts.

4.4. Order of magnitude of potential soil carbon stocks and uncertainties

The conversion of arable land into forest and permanent grassland displays considerable potential, of about 0.5 tC/ha/year over 20 years. The changes in practices which have been retained (suppression of tillage, planting of green fertilisers or catch crops) make a smaller contribution to carbon accumulation of about 0.15 to 0.3 tC/ha/year. The potential for carbon accumulation in grasslands may also be important: different changes to fodder cropping systems could enable a flux of 0.3 to 0.5 tC/ha/year.

These values were obtained by selecting references which corresponded to pedoclimatic conditions similar to those in France, and presenting the most reliable experimental evidence. They should nevertheless be considered with caution, given the limits described below.

TABLE 1. EVALUATION OF CHANGES TO LAND USE OR MANAGEMENT PRACTICES LIKELY TO INCREASE CARBON STOCKS

Anticipated and real effects** Habits/practices	Effect on OM input (changes to primary production and/or % supplied to the soil)	Effect on OM output (rate of mineralisation)	Other positive environmental effects	Negative secondary environmental effects	Assessment (retained or not as increasing carbon stocks)	Additional stock accumulation (20-year scenario)
Arable land						
No-tillage	*may slightly ↘ production* *↘ slightly level of OM conversion into humus*	↘ rate (increased protection of OM)	↘ erosion	↗ use of pesticides ↗ emission of N2O, to be confirmed	retained	0.2 ±0.13 tC/ha/year
Restitution of crop residues	↗ % restored to the soil	-		-	already performed: less value than valorisation as energy	0
Restitution of animal waste	exogenous OM input ↗ production by fertilising effect	*may ↗ rate through the input of N*		if excessive inputs	already performed nil balance	0
Intermediate crops (green fertiliser)	↗ lannual production and % returned (crop not harvested)	-	↘ nitrate leaching ↘ erosion		retained	0.16 ±0.08 tC/ha/year
Increased fertilisation	↗ production	↗		risks of pollution (nitrates, N_2O)	not retained	0
Irrigation	*little to gain if already intensive system*	*↗ by prolonging the period of mineralisation*		consumption of water, risk of nitrate leaching	not retained	0
Exogenous organic inputs	input of exogenous OM ↗ production by fertilising effect	↗		presence of metal trace elements	few "reserves" of OM negligible	ε on average
Sowing to grass of vines and orchards	↗ annual production and % returned (cover not harvested)	↘	↘ erosion	-	retained	
Conversion into permanent grassland	↗	↘	↘ pollution, ↗ biodiversity, etc.	-	retained	0.49 ±0.26 tC/ha/year
Afforestation	↗	↘	+ stocks in woody biomass	closure of landscape	retained	0.44 ±0.24 tC/ha/year
Grasslands						
↗ duration of TG + planned intensification	↗	↘	no-tillage effect	-	retained	0.1 to 0.5 ±0.25 tC/ha/year
Conversion of TG into PG with ≥ intensification	↗	↘	↗ biodiversity ↘ pollution	-	retained	0.3 to 0.4 ±0.25 tC/ha/year
Moderate intensification of poor permanent grasslands	↗ production	-		-	retained except for mountains and wet regions	0.2 ±0.25 tC/ha/year
Afforestation	↗	↗	+ stocks in woody biomass	closure of landscape		0.1 tC/ha/year
Planting of hedgerows	↗	↘	↗ biodiversity, etc.	-	retrained but highly variable effect	0,1 ±0,05 tC/ha/an

** Italics imply no or unfavourable effects on stocks ; TG : temporary grasslands ; PG : permanent grasslands.

Uncertainties and variations

The stock fluxes retained are modal values for the country: they should be considered as having a relative uncertainty of about 50%, linked in particular to the insufficient numbers of long-term studies in France or Western Europe. The very considerable variations in annual increases in carbon stocks also tend to demonstrate that practices do not have a univocal impact, as their effects depend upon the interaction of numerous factors.

Emissions of non-CO_2 greenhouse gases

The results obtained will be highly sensitive to the effects on non-CO_2 greenhouse gas fluxes induced by changes in practices, particularly when these changes affect the nitrogen cycle and possibly the emissions of N_2O.

Reversibility

Because soil carbon release is more rapid than its accumulation, the benefits to be expected from adopting practices which enhance accumulation will be reduced if these practices are not sustained. Thus, for national accounting, not to take account of practices which cause a release of soil carbon could result in serious bias. In terms of strategy, it may therefore be more important to conserve existing stocks than to try to create new ones.

Climate change effects

The potential effects on the carbon cycle of climate changes and the composition of the atmosphere, which are not taken into account in these estimates, represent a further uncertainty.

Global warming and increases in atmospheric CO_2 are likely to increase plant production and hence the restitution of OM to the soil; however, the rise in temperature will also accelerate mineralisation. The balance between these two contrary effects will probably not be negligible: it may cause changes in carbon levels of between +2 and –2% for the 20 years to come, depending on which of these phenomena predominate, or a net carbon flux of between +1.5 and -1.5 MtC/year for French agricultural land alone.

Moreover, climate change may, in some cases, call into question the options chosen to enhance soil carbon stocks: for example, an increase in the frequency of droughts may lead to an abandonment of sowing to grass in vines and orchards in the South of France, or a reduction in the productivity of permanent grasslands, thus encouraging a change to annual crops harvested in the summer.

5. CARBON ACCUMULATION SCENARIOS AT THE SCALE OF MAINLAND FRANCE

The aim is to test the usefulness of changes in land use or farming practices on a national level by simulating the accumulations achieved according to different scenarios, dependent upon the practices chosen.

5.1. Method

For each change in use or farming practice, an increase in accumulation at a national level is calculated based on the accumulation curve per hectare (obtained using the exponential equation in Figure 4) and spatial extension hypotheses concerning this change. These surface areas are proposed with reference to the areas which might be concerned (determined on the base of the Agricultural Census, 2000), and then by formulating hypotheses concerning a more limited extension to the practice and integrating the constraints on its implementation.

Example of adopting no-till

The 18 million hectares of land covered by annual crops could be concerned by this practice. Its possible extension is limited to 70% of this surface area, as about 30% of arable land is not suited to no-till.

The hypothesis of a simultaneous change on 20% of arable land to no-till would produce additional carbon accumulation of 0.55 MtC/year over 50 years and 0.7 MtC/year over 20 years. Since it is unlikely that this type of conversion could be achieved immediately, a more realistic hypothesis is used, that of its gradual adoption over a period of 20 years. The hypothesis of a periodic tillage, on average once every four years, is also envisaged.

TABLE 2. HYPOTHESES AND RESULTS OF SIMULATIONS ON ADDITIONAL CARBON SEQUESTRATION.

Change in land use or practice	Mean annual additional storage per hectare (20-year scenario)	Constraints in terms of agronomic feasibility and applicability	Potential surface area retained for the estimate	Additional annual stocks for mainland France (20-year scenario) in millions of tonnes carbon/year	Possibilities for verifying surface areas involved	Possibilities for verifying carbon stocks
Afforestation of agricultural land	arable → forest: 0.5 tC/ha/year grass → forest: 0.1 tC/ha/year	Will mainly affect low potential land (except afforestation of set-aside)	from 30,000 to 80,000 ha per year - from arable land………....................... - 80% of fallow and grassland and and 20% of arable land .... (the current rate of increase in forested areas is 80,000 ha/year)	.......0.15 to 0.40 M tC/year ....0.04 to 0.10 MtC/year	Feasible using remote sensing	requires organisation of supplementary observation sites
Conversion of arable land into permanent grasslands	0.5 tC/ha/year	Can only affect land belonging to animal farms	from 10,000 to 80,000 ha per year…… (90,000 ha/year for 20 years = restoration of permanent grassland lost since 1970)	.......0.06 to 0.45 MtC/year		
Sowing to grass in vines and orchards	0.4 tC/ha/year	Competition for water	Base: 1 Mha of vines and orchards adoption on 20 to 50% of surface area...	.......0.08 to 0.20 MtC/year		
Adoption of direct drilling	0.2 tC/ha/year	Control of weeds and pests Constraints linked to soil, compacting	Base: 18 Mha of arable land, gradual adoption, over 20 years, on 20 to 50% of crops …...………….................. + hypothesis of tillage every 4 years….....	.......0.4 to 1 MtC/year ....0.23 to 0.58 MtC/year	Very difficult without a declaration system	Becomes easier as the surface area under direct drilling increases. Problem with baseline
Planting of intermediate crops	0.16 tC/ha/year	Relatively long period between crops (before spring sowing) Competition for water with subsequent crop Organisation of work Management of long-term effects	Base: 4 Mha in spring crops adoption on 0.5 to 2.5 Mha …………....	.......0.07 to 0.33 MtC/year	Feasible using remote sensing, but costly (annual checks)	Difficult: problem with baseline

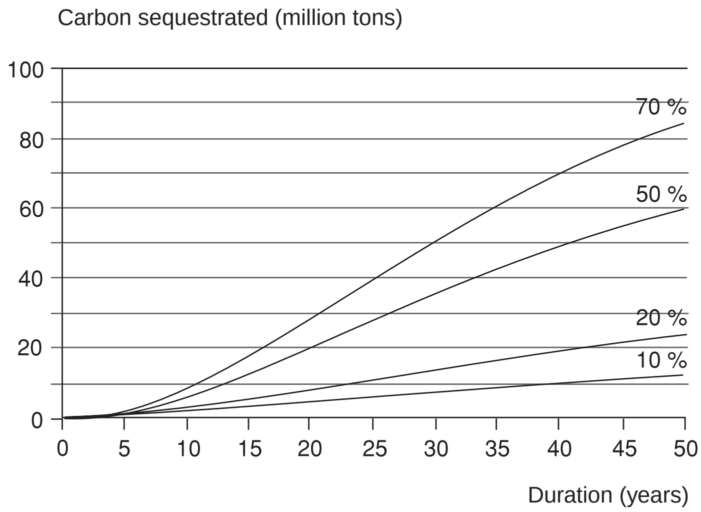


Figure 6. Simulation of additional carbon accumulation in French arable land under the hypothesis of a gradual conversion to no-till over a 20-year period.

Hypotheses concerning the conversion of 10, 20, 50 and 70% of arable land.

The same procedure is applied to other changes in land use or practices (see Table 2). The Expert Report thus provides elementary scenarios which should be combined to calculate the total increase in accumulation expected under scenarios for the different practices.

5.2. Accumulation potential according to different scenarios

In view of the history of changes to land use, and notably the extension of forested areas, French land has always exhibited an increase in C stocks since 1850, except for a short period during the implementation of European bare set-aside land procedures. For the period 1980-1990, the net accumulation flux is estimated at 1.5 ±0.5 MtC/year (or 0.03 ±0.01 tC/ha/year).

An extreme scenario for land use changes, corresponding to the conversion over a 10-year period of 3 Mha of arable land and 0.8 Mha of set-aside (or a total of 3.8 Mha), half into permanent grasslands and half into forestry, would enable an additional accumulation of 2.9 MtC/year over 20 years.

A more realistic scenario, or:
- 50% of arable land converted to direct drilling in 20 years, with tilling on average once every 4 years: 0.6 MtC/year
- the planting of intermediate crops on all possible land, or 4 Mha: 0.6 MtC/year
- 30,000 ha/year of afforestation (80% on fallow and grasslands and 20% on arable land): 0.1 MtC/year
- 30,000 ha/year conversion from arable to permanent grassland: 0.1 MtC/year

would produce an additional accumulation of 1.4 MtC/year over 20 years.

This estimate does not include additional accumulations due to changes in the management of fodder systems, which are more difficult to quantify.

➜ It is necessary to retain a more probable order of magnitude of 1 to 3 MtC/year for potential additional carbon storage for the next 20 years, for the whole of mainland France.

These scenarios give rise to markedly lower estimates than those found by other authors in Europe. These differences mainly arise from:

- a generally lower evaluation of carbon accumulation fluxes per surface unit, based on references which either correspond to the conditions prevailing in France, or conclude on less potential due to different hypotheses.

- a more restrictive assessment of the areas potentially concerned by changes in use or practices, if account is taken of current land use at a national level and major trends (reduction in grassland areas, etc.), as well as problems with regards to agronomic feasibility, etc. ;

- account being taken of the fact that it may be difficult to apply some practices continuously (for example, interruption of direct drilling by occasional tillage).

Even the moderate hypothesis of carbon accumulation reaching about 1 to 3 MtC/year would only be possible if the changes made affected more than half of all farmland:
- the changes to farming practices envisaged are considerable;
- the hypotheses concerning the areas affected by changes in use go counter to mainstream practices, particularly regarding the conversion of arable land into grasslands and forests. The conversion to grassland would imply heavy changes in forage production and livestock farming systems.

It should also be noted that:

- this accumulation potential is limited in time and space. It is therefore a finite solution, which may allow a certain flexibility with respect to the Kyoto commitments but in no case constitutes a sustainable, long-term solution, as our knowledge stands at present.
- the knowledge and data available at present are insufficient to enable a spatial estimate of carbon accumulation potential in the land. In fact, major regional disparities can be anticipated as a function of pedoclimatic conditions (clay content, soil water status, etc.) and current carbon stocks and dynamics;
- a complete environmental assessment of some practices (particularly the greenhouse gas budget concerning no-tillage) is still to be made.

6. ACCOUNTING AND VERIFICATION OF SOIL CARBON STOCKS

6.1. Rules governing the application of the Kyoto Protocol

- Accounting rules

We must recall that only intentional additional accumulation will be taken into account, resulting from voluntary actions undertaken since 1990. If measurements are based on the "net-net" accounting system, accumulations will be calculated by subtracting from the fluxes for the five years 2008-2012 the value of the flux in 1990 multiplied by 5.

Application of these rules will be rendered difficult by the fact that the current geographical extension of many of the practices eligible under the terms of Article 3.4. is still not known with precision, and in general no statistics are available on this subject for the year 1990.

- Rules for verification

The procedures proposed usually involve verifications which can be broken down as follows:
- verifications of the accumulation by surface area induced by a practice, based on measuring local variations in carbon stocks (achieved by sampling and/or numerical modelling) and on the periodic monitoring of reference sites which include control plots and others subjected to a change of use or practice;
- verifications of the surface areas concerned by these changes in use or practice, performed for example using remote sensing methods.

The level of stringency required for these verifications has not yet been fixed by parties to the Convention.

A strict verification implies sampling at the beginning and the end of the commitment period on each area subjected to an activity defined under Article 3.4., and a comparison with a sufficient number of samples from control areas. The data obtained will be aggregated to produce an estimate on a national level. Other methods will also be necessary to produce a second set of independent data for verification. Such procedures are difficult to implement on a national level and their cost will probably be prohibitive.

In contrast, if a less demanding verification procedure were retained, the estimate of the surface areas concerned would not be georeferenced, and default values for changes in carbon stocks induced by each practice would be used to estimate the effects of an activity on national carbon stocks. However, even an estimate of the surface area concerned by a given activity may prove to be unverifiable if no geographical references are available.
An intermediate level of stringency would lead to verifications based on a georeferenced inventory of the surface areas concerned (by remote sensing or determinations in the field) to enable an estimate of changes in carbon stocks based on experiments (in representative regions in terms of climate and soil), observations on reference sites or well-established, documented and archived models.

6.2. Applicable procedures for the verification of carbon accumulation

It is in this context of an intermediate level of stringency that the feasibility of verifications, and notably the relevance of existing tools, have been examined.

● Verification of carbon accumulation per unit surface area

Measurements of changes to carbon stocks

The considerable variability in annual carbon accumulation and in the carbon pool itself, and the sustained effects of ancient use, make it difficult to demonstrate low relative changes in carbon stocks over a short period (5 years). In addition, any accumulations need to refer to a moving baseline given the continuous and spontaneous development of land uses and techniques, and the effects of climate change. Because of spatial variations, the number of samples and analyses necessary to certify changes in soil carbon stocks may be very high.

Long-term experiments (particularly useful when studying mechanisms for the accumulation/release of carbon in the soil) are not sufficiently numerous in France or in the world to reflect the diversity of agricultural and pedoclimatic conditions. The monitoring of reference sites will be necessary, which will require dense coverage of the entire country and extremely precise georeferencing of these observation sites.

The capacity of a network similar to the Soil Quality Measurement Network* (which is currently being set up and comprises 2100 observation points spread over the country, devoted to monitoring soil quality) to supply proof of additional carbon accumulation during the commitment period, has been tested. Knowing the proportion of different land uses in France, the distribution of present carbon stock values by type of use and soils, and running hypotheses on the kinetics of these stocks, it was possible to simulate the results of successive measurement campaigns, and thus to test the ability of the network to detect a significant change in stocks. Under the different scenarios for changes in practices which have been tested, the mean periods necessary to detect a change in the soil carbon pool range from 3 to 15 years; in unfavourable scenarios, these periods can reach 10 to 25 years. To obtain the information required, it is necessary to ensure an increased density of the network and/or the implementation of specific monitoring dedicated to certain uses, thus raising the central question of the cost of setting up such a network and then the completion of all verifications. If changes in practice are rapid and numerous, the number of sites needed to monitor carbon stock kinetics will soon become prohibitive.

The verification of carbon accumulation induced by different activities would require:

- an increase in the number of long-term agronomic studies to enable calibration of the models under varied agricultural and pedoclimatic conditions;
- the development of a systematic monitoring network (or one dedicated to certain changes) to obtain statistical evaluations and tools to validate the predictions supplied by models;
- the use of observations on long-term plots which already exist locally, even if they need to be supplemented by specific analyses;
- in order to respond to the baseline issue, the setting up of control sites;
- the development of spatialisation techniques and/or inventories providing access to input parameters for the models;
- to bridge the gap between measurements and models at different scales, and to progress in the generalisation of local models and techniques for the inversion of global models.

Methods for the measurement of CO_2 fluxes

These methods, which consist in measuring gas exchanges between the ground and the atmosphere, have the advantage of supplying data which are independent of those obtained by measuring soil carbon stocks. However, they do have several limitations: they require a costly infrastructure and few sites are as yet equipped (approximately twenty sites in Europe on agricultural land); they do not reflect accumulations in the soil because the amounts measured also include the CO_2 stored in biomass, including that which is released at harvest.

The IPCC report notes that the reliability of these methods is insufficient at present to constitute a basis to estimate accumulation, but on the other hand they may serve as an independent method for verification.

TABLE 3. INVENTORY AND SURVEY DATA WHICH COULD BE USED TO MONITOR LAND USE AND AGRICULTURAL PRACTICES

	Census	Remote sensing	Aerial photographs	Inventories in the field		Surveys of farmers	Declarations by farmers and follow-up	
Operation	RGA	CORINE Land Cover	National Forestry Inventory (NFI)	TERUTI survey	LUCAS European survey	SCEES survey	For PAC premiums	FFYFC dossier and monitoring
Type of data	Use of agricultural land by farms	Land use	Land use, forestry practices	Land use	Land use (extension of TERUTI EU)	Agricultural practices for 10 crop types (incl. temp. pasture) + set-aside	Use of arable land and/or fodder areas only	Crops and practices over 5 years for plots under contract
Number/type of categories	By crop	44 types, of which 12 agricultural	Few types for land outside forests	By crop	by crop	For 10 crop types + set-aside	By crop	By crop
Frequency Dates	Every 10 years The last one performed in 2000	10 years Performed in 1992	About every 10 years	Annual	Annual	Every 4/5 years The first in 2001 Arable crops in 1994	Annual	Depending on measures chosen
Scale of acquisition Magnification	At a farm level	30x30 m	Aerial photographs + sample plots	1 point/100 ha (= 550 000 points) constant sample (over a timespan of 10 years)	Observation points (100,000 for the entire EU) + transects	Sub-sample of TERUTI sample points	Ranges from plots to farms	Declared déclarées plots within a farm
Aggregation of data available	By administrative division (bias: location of farm office)	250x250 m numerous mixed pixels	Small forestry regions. Localisation of data possible	Small agricultural regions. Localisation of data possible	Region level départemental ou régional	Not currently known (under analysis)	Administrative division (bias: declarations only)	Records held by farmers → difficult access
Georeferencing	exhaustive	Exhaustive	Exhaustive	On samples only	On samples only	No	No	Based solely on FFYFC declarations
Transition matrix	No	Yes for principal uses		Yes for all uses	Yes	Yes	Reconstitution of successive crops may be possible	Yes for all uses and practices

- Verification of surface areas

This verification is not possible if georeferenced data are unavailable. Several methods have been envisaged to account for and georeference the surface areas subject to changes in use or practices (see Table 3: Evaluation of existing systems):

- **Inventories**, which may be exhaustive or based on samples representative of the country

Inventories have the advantage of supplying systematic data (including on changes which induce carbon release). They can be performed using remote sensing with respect to changes in use or certain practices; the information gathered is then exhaustive; checks several times a year are possible but expensive. The identification of other practices (no-tillage, etc.) requires observations in the field; this type of plot-based identification would be evidently restricted to sample areas.

➜ No inventory programme exists in France which allows a precise georeferencing of all changes in land use, or a periodicity which allows monitoring over the commitment period.

- declarations by farmers

This is the method used for CAP premiums or for French Land Management Contracts (LMC); it is accompanied by a control procedure in the field of the truthfulness of the activities declared, on a reduced sample of declarations.

➜ CAP declarations and LMCs do not concern all farmers, which raises the questions of how representative these data may be and the problems encountered in their extrapolation.

To produce a verification of the surface areas subject to these activities, it is necessary to:
- develop methods which will provide information on land use change matrices which is precise and based on a short period of time;
- develop the monitoring of practices based on inventories, surveys or contractual commitments by farmers.

➜ If the aim is to draw up a reliable and verifiable account of soil carbon accumulation over the period of the commitment, the investment required is considerable, and there must be fears that the cost of a complete verification will exceed the benefits anticipated in terms of CO_2 sequestration.

➜ The measures which are the easiest to verify and which will ensure the largest unit accumulation of soil carbon are those concerning major changes of use such as the conversion of arable land to forests or grasslands.

7. ECONOMIC POLICY TOOLS WHICH COULD BE USED TO ENCOURAGE PRACTICES FAVOURING CARBON ACCUMULATION

It is necessary to determine the methods to be used by national authorities to encourage farmers to adopt practices which will ensure a higher level of soil carbon accumulation. Economic analysis supplies tools which can evaluate the adequacy of existing regulatory instruments to this objective, and notably their economic efficacy, i.e. their ability to induce the highest additional storage at the lowest costs.

7.1. Theoretical context

The search for efficiency leads policy makers to use **cost-benefit analysis.** Such an analysis aims to evaluate in monetary terms the individual advantages and disadvantages which can be drawn from a collective decision, while ensuring that none of the direct or indirect effects are forgotten. It thus provides a grid to analyse the different regulatory instruments, the conditions required to define their implementation and efficiency and their possible impact.

- Externality and internalisation instruments

CO_2 emissions and increasing carbon sinks constitute externalities* which are respectively negative and positive. By definition, externalities are not taken into account spontaneously by the market, and their internalisation may require State intervention. The regulation of externalities is often based on the "polluter pays" principle, which consists in taxing those agents responsible for deteriorating the quality of the environment; if applied to a positive externality, this principle results in remunerating the agent which produces amenities for the good of the community.

The instruments which make it possible to encourage agents to integrate in their individual decisions effects which they do not spontaneously take into account are based on a dual logic: standards (affecting the products or the process) and economic instruments (taxes, subsidies, emission permits market). The latter have the advantage of allowing a decentralisation of optimum choices in terms of abatement. These different instruments vary in terms of their usefulness and limitations, but to different degree, they all suppose knowledge of the cost of pollution damage attributable to pollution, of the benefits associated with reducing pollution and the costs of pollution monitoring and/or ensuring compliance. In this perspective, calculations must be available on the different aspects making up the cost-benefit analysis.

7.2. Difficulties encountered in evaluating the costs and benefits of carbon accumulation

Evaluation of the cost of additional carbon accumulation

These costs include those linked to changes in practices (direct and indirect costs of the additional storage itself; adjustments and opportunity costs, etc) and those linked to implementing normative systems and economic instruments (transaction costs linked to verifications; impact on markets and prices, etc.).
The lack of references and the diversity of pedoclimatic and agricultural situations, which induce considerable variations in the efficiency of carbon accumulation and its costs, make it even more difficult to quantify these costs and the benefits linked to additional storage in agricultural land. With respect to direct costs, a pragmatic solution consists in basing evaluations on a regionalisation of additional storage scenarios which takes account of this diversity. A preliminary approximation of costs is then obtained by simulating the loss of income associated with adopting different accumulation-enhancing practices; these costs are then compared with the carbon balances attained in each case. The difficulty arises with respect to collecting economic data which are coherent with the reality of processes at a pedological level. In addition, because of the dynamic nature of carbon storage, evaluation of these costs must integrate the temporal dimension and history of these practices.

Measurement of costs and potential for abatement in the agricultural sector

Few economic studies have evaluated the specific costs of additional carbon storage in agricultural land, most of them having addressed their "forestry" aspects. Nevertheless, a few studies have included this aspect in broader evaluations, covering the different sources and sinks of greenhouse gases from agriculture. They are based on models which couple simulations of the technical and economic functioning of farms and wide-ranging assessments of different greenhouse gas sources and sinks.
This is the case of a study which looked at the American agricultural sector and supplied an evaluation of the costs of abatement and potential net reductions in CO_2 emissions for different values of a ton of carbon. This study showed that the efficiency of actions which could be envisaged to reduce these emissions were strongly dependent upon the value of a ton of carbon; at values below $50, the accumulation of carbon in agricultural land was an economically viable option, but at higher values, afforestation strategies and the production of biofuels proved less costly.
A similar study was performed in France. It confirmed the major disparities existing in the individual costs of abatement, and demonstrated the important impact of authorisations for forest plantation on set-aside land. This measure would allow a marked reduction in the total cost of abatement (and thus increase the potential for an economically efficient reduction) but it is not neutral in terms of redistribution of the abatement costs (breeders bearing the major costs of abatement). It also showed that an accumulation of carbon in agricultural soils could make a marked contribution to improving the greenhouse gas budget, but nevertheless this was relatively less important than the potentials obtained by afforestation or reductions in methane emissions.
Specific research on the costs of accumulating carbon in French agricultural soils still needs to be performed. The models which need to be developed must take account of interactions with other greenhouse gas emissions, the characteristics and dynamics of carbon accumulations and the possible strategic behaviour of farmers (need for recourse to instruments which may be less effective but also less costly in terms of public control, aimed at preventing fraudulent behaviour).

Control of the effectiveness of accumulation

Economic regulation – whether this implies a standards system, taxes/subsidies or transferable quotas – must be based on instruments which can control and verify individual activities which allow a distinction between natural variations in carbon stocks and those induced by voluntary actions.

From an efficiency standpoint, it is important that the incentives implemented should be active as close as possible to the source of the amenity. Thus, in theory, a premium per ton of carbon accumulated appears preferable. However, in the case of carbon accumulation, the cost of an individualised and reliable system for control and verification may make so-called "second best" solutions more attractive, which make premiums rely on less variable criteria such as practices or surface areas. It is then possible to envisage integrating these measures at lower cost in systems such as the CAP.

The benefits linked to carbon accumulation

A direct evaluation of these benefits is very difficult because of the considerable uncertainty concerning the degree of climate change and the costing of its potential for harm, as well as that share which must be attributed to anthropogenic changes in the composition of the atmosphere.

The principle of an international market for Certified Emission Reduction (CER) credits having been accepted, this approach may provide a quantified assessment of the value of a ton of carbon to be retained for analysis. The ranges of estimates resulting from simulations of the functioning of such a market are still very broad (from less than $10 to $150 per ton). Let us suppose a value of €80. In the knowledge that the most efficient changes in practice allow additional stocks of 0.3 tC/ha/year, an additional storage subsidy could not at best exceed €24/ha/year (verification costs not substracted), to be compared with the €400/ha direct European grants proposed for the principal crops.

➜ As current methods of control stand, it is technically and economically impossible to base a system of taxes or incentives on CO_2 emissions or additional soil carbon storage. We are forced to base any system on agricultural practices and land use and on the surface areas concerned (the situation differs from the emission of N_2O, which can be associated to the use of a product, which is legitimate – if we accept the hypothesis of small variations in emission factors – the taxing of fertilisers).

➜ Basing the remuneration of additional carbon storage on the mean stock coefficients obtained using predetermined practices and the value of a ton of carbon raises two problems:
- firstly, such a system implies neglecting, at least in part, the spatial and temporal variability of accumulation coefficients,
- and secondly, temporal variations in the value of a ton of carbon (fixed for the entire economy) is little compatible with the long-term actions which are difficult to reverse which would have to be undertaken by farms in order to significantly increase carbon accumulation.

7.3. Possible incentive measures

Standards

Recourse to a standard would involve fixing a floor limit, i.e. a minimum quantity of carbon which must obligatorily be accumulated in the soil, per farm or per unit surface area. Because a poor assessment of costs and benefits is a source of inefficiency, the principal problem therefore concerns fixing the optimum level of carbon accumulation required.

In addition, recourse to a standard does not encourage agents to try and obtain a level of positive externality higher than the floor limit. Indeed, on the contrary, this would encourage fraud, so the system requires a system of rigorous and frequent controls, associated with a dissuasive system of penalties.

Subsidies

Subsidy systems have the advantage of encouraging agents to attain accumulation objectives at the lowest cost, so they therefore constitute a dynamic incentive for innovation.

The problem is to set a base for the premium which is sufficiently well-correlated with the results anticipated, but without involving prohibitive control costs. A per-hectare subsidy, allocated when a practice reputed to be accumulation-enhancing is adopted, could be efficient, on condition of finding a solution to the problems of geographical variations in carbon accumulation capacities associated with the different practices.

Any subsidy system, insofar as it is funded by the tax-payer, can also raise problems of social acceptability if it is not supplemented by an environmental tax on activities which generate greenhouse gas emissions.

Inasmuch as it is supplementary stocks which need to be taken into account, subsidies for adopting practices will necessarily exclude those farmers who adopted these practices previously. Although this aspect is not problematic in terms of efficiency, it may be a source of problems regarding the social acceptability of such measures, and cause people to wait before implementing any changes.

The market for emission permits

It is possible to imagine that the principle of a market for certified emission reduction (CER) credits, decided on an international level, could be extended to individual agents. This system has the advantage that the objectives fixed can be attained (the objectives being to define the global number of credits granted) at a lower cost if the credits are negotiable in a fully competitive market. It also avoids the need for prior knowledge of the costs of abatement, since the interactions between sellers and purchasers mean that in theory, a price per ton of carbon will be fixed which will assure minimisation of the total cost.

A first problem arises with respect to the initial distribution of the credits granted. Although efficiency is not called into question in this case, the allocation of initial credits may raise problems of social acceptability; if they are granted as a function of past practices, agents who are already "virtuous" will be penalised. A second difficulty is establishing a market which can function freely and competitively. Finally, the control problems referred to above remain, because the additional soil stocks "exchanged" on the basis of credits must be efficient, controllable and reliably confirmed.

Specificities linked to carbon storage in agricultural soils

- Carbon storage and release dynamics in the soil require that practices favouring sequestration must be applied continuously and over a long period to be effective. Incentive measures must therefore be laid down in the context of long-term contracts with farmers. Such contracts induce supplementary opportunity costs inasmuch as they reduce the choices available under such a commitment.
- To prevent "leakage" ("leaks" through CO_2 emissions or carbon loss induced by adopting one accumulating-enhancing practice), eligibility for a grant must be included in an overall assessment of greenhouse gas emissions from the farm.
- The incentive systems set up must be coherent with the institutional systems already in place. In particular, conflicts between measures covered by the CAP and incentives for carbon accumulation must be limited.
- The adoption of measures to encourage carbon accumulation in agricultural soils may increase the disparities existing between farms, particularly between animal breeders and cash crop farmers (carbon subsidies going to farmers with considerable resources in terms of surface area, and taxes on methane emissions weighing on animal breeders). Once again, this consideration does not concern the economic efficiency of the measures to be implemented, but their social acceptability.

➜ The most appropriate method seems to be a comprehensive, farm-based individual contract. Such a contract could be inserted in contracts of a LMC type. Although it has not been shown that it is more economically efficient than a uniform measurement, such a system would have several advantages: it is based on a diagnosis and an individualised project, it involves the producer, it takes account of the entire farm strategy, it ensures coordination between "purely" agricultural aspects, other environmental concerns (water pollution, management of animal waste, etc.) and incentives for carbon accumulation. So as to prevent any leakage, such a contract must include conditions which encourage a reduction at the same time in other sources of greenhouse gas emissions. Of course, this contract option supposes that a large number of farms and a large proportion of French land would be involved, and that the lasting nature of the contract would be credible. Regionalised standard contracts would make it possible to reach a compromise between taking sufficient account of pedoclimatic variations and the cost of controls. Finally, such an option is well suited to a European agriculture policy which must increasingly base its justification on environmental aspects.

8. REVIEW AND CONCLUSIONS

A carbon accumulation potential which is not negligible but difficult to valorise

The Assessment Report shows that by changing land use and/or certain agricultural practices, it is indeed possible to increase significantly the accumulation of organic carbon in French agricultural soils. From the different scenarios tested, it appears that the maximum potential for enhancing carbon stocks is about 3 to 5 million tons of carbon per year over a period of 20 years. A combination of more realistic hypotheses concerning the adoption of practices which enhance carbon accumulation produces an increase of about 1 to 3 million tons per year.

It is specific changes to land use which will enable the highest accumulation fluxes per unit surface area: afforestation and an increase in permanent grasslands. Afforestation also induces increased accumulation in the woody biomass and a reduction in inputs and energy consumption. Because of the surface areas involved, some farming practices also suggest significant potential efficacy: the suppression of tillage and the use of shallow ploughing, the planting of green manures between crops, sowing grass between rows in vines and orchards. The planting of hedgerows or changes to the management of permanent and temporary grasslands, where the effects are more difficult to quantify, may also contribute to enhancing carbon stocks. In contrast, the opportunities offered by the management of agricultural or urban residues or agricultural waste appear to be small, and an intensification of crops which already have a high yield produces no benefits.

This global potential, estimated for the conditions prevailing in France, is smaller than that suggested by other experts. However, although it is only equivalent to 1 to 2% of French greenhouse gas emissions, it is not negligible, as it may represent a large proportion of the efforts required to comply with the commitments to the Kyoto Protocol.

However, realising the potential of carbon accumulation will come up against numerous uncertainties and problems.

Uncertainties and the variability of carbon pools

- The carbon accumulation potentials retained must be seen in the light of marked relative uncertainty of about 50% concerning unit fluxes, and more in terms of the national estimate.
- The results are highly sensitive to pedo-climatic and local agricultural conditions, and thus markedly contrasted as a function of regions.
- The estimates made do not take account of the emissions of other greenhouse gases (notably N_2O) induced by the adoption of practices enhancing carbon accumulation, which must be deducted from the sequestration of CO_2.
- Actual storage may be smaller if climate change has an effect on increasing mineralisation, or if they prohibit certain options which imply high water consumption.

Conditions of implementation

- The carbon accumulations envisaged imply massive changes to practices and land use, some of which run contrary to current evolutions (trend towards reducing permanent grasslands, etc.) or require important choices in terms of agricultural policy (afforestation of fixed set-aside land, etc.).
- They suppose commitments by farmers for a very long period (so as to build up additional stocks and then maintain them), which will be particularly difficult to obtain because of the likelihood of rapid developments in the political and economic context of agriculture.
- To be taken into account in the national balance, they will require a complicated system of verification, which will therefore be costly to implement.
- They will require incentive measures, the type, criteria of allocation and funding of which are not easy to define.

Technical conditions for verifications

- The demonstration of highly variable increases in additional storage, which will be very small when compared to the broad variability in stocks themselves, will be difficult and require the implementation of costly observation systems.
- The obligatory determination of a baseline will be particularly difficult to achieve.
- Changes in practices and their effects will be intrinsically more difficult to observe and quantify than changes to land use.

- The procedures might be technically impossible to implement for the first commitment period, and if the level of verification is too demanding, its cost will become prohibitive when compared with the price of a ton of carbon.

Unlike reductions in emissions, the accumulation of soil carbon does not constitute a permanent solution to reducing atmospheric CO_2 levels, since stocks will cease to grow after a few decades, and the agricultural land which can be used is finite in quantity.
On the other hand, an increase in accumulation may allow some degree of flexibility with respect to the commitments made in the context of the Kyoto Protocol, and usually be accompanied by connected agricultural and environmental benefits.

The need to envisage a global policy with respect to the greenhouse effect, to be integrated in broader agricultural and environmental policies

In view of the uncertainties concerning its results, the constraints affecting its implementation and the probably low cost of a ton of carbon when compared with existing agricultural subsidies, **a specific policy, restricted to carbon soil accumulations, seems difficult to achieve and little effective. Measures aimed at increasing carbon accumulations should be integrated into a broader policy.**

A global policy to fight against the greenhouse effect should make it possible to:
- take account of all greenhouse gases of agricultural origin, and notably emissions of N_2O. This latter point should lead to considering also the management of nitrogen inputs as a priority, rather than the management of carbon only. Indeed, a 10% reduction in nitrogen fertilisers would already correspond to a gain of about 0.6 MtC/year (emission of N_2O and synthesised energy);
- ensure that adopting a practice in an area does not induce any emissions or carbon leakage elsewhere;
- compare carbon soil accumulations with energy alternatives (crops for the production of biofuels and energy valorisation of agricultural and urban residues);
- and compare these with the emission reductions possible in other economic sectors.

Practices which tend to accumulate carbon in the soil almost always engender **other environmental benefits:** limitation of erosion, improvements in soil and water quality, economies in fossil energy, greater biodiversity, etc. This compatibility with other environmental objectives allows the integration of carbon incentive measures in broader agricultural and environmental policies adopted in the context of the CAP. The existence of certain negative effects (increased use of pesticides with no-tillage, closure of landscapes) will nevertheless require certain choices between environmental objectives.
Reciprocally, agricultural and environmental policy actions (integrated agriculture, soil protection, biofuels, etc.) may be accompanied by benefits in terms of carbon accumulation. If it is possible to demonstrate the intentional nature of these gains, they could be claimed as actions in application of the Kyoto Protocol; such recognition of global agricultural and environmental policies including actions on carbon is necessary to the implementation of these actions.

Any policies of this type will necessarily have a strong national dimension. They should be justified in the light of local environmental and land needs, taking account of the effective functional units which go beyond the plot (farms, watersheds, catchment areas of ground water aquifers, etc.).

The need to develop research and acquire references

The critical examination of the French and international literature which was done for this Assessment Report underlined the gaps in our knowledge and/or the impossibility of precisely quantifying some of the processes. This situation results in estimates which are accompanied by a considerable uncertainty, and the impossibility in specifying with sufficient precision the pedoclimatic and agricultural conditions which ensure the efficacy of measures aimed at increasing carbon stocks. Such a potential, if sufficiently important when compared with the abatements necessary, could in the long term be valorised effectively if situations offering the best conditions can always be identified, and if economical and reliable methods to quantify the gains achieved can be developed. It is therefore necessary to pursue research and acquire additional references in several areas. The challenge goes far beyond the immediate question of French implementation of the Kyoto Protocol. It is clear that it must be seen in the context of global, long-term management of the problem of the greenhouse effect and a more exact description of the sink and source functions of soils. The importance of the soil fluxes concerned, when concerned with the atmospheric CO_2 budget, justifies the research which should be devoted to their future.

Knowledge of carbon biotransformation mechanisms in the soil

Some processes are still poorly understood or insufficiently studied in a range of situations which is too limited to allow a generalisation of results. This is notably the case for rhizodeposition, the effects of physicochemical factors and the physical protection of organic matter, the very long residence times of some carbon pools and the sink function of soils for methane, etc.

A clearer understanding of these processes would also provide opportunities for the design of novel practices aimed at increasing the soil carbon pool.

Global modelling of carbon behaviour in the soil and broader national projections

The complexity of mechanisms and the multiplicity of factors and interactions require the use of models for the dynamics of carbon, in order to predict its evolution.

The calibration of models will require the development of long-term observation systems under experimentally-controlled conditions in the field, as well as in natural situations, so as to acquire knowledge under diversified pedo-climatic and agricultural conditions. The use of spatialised estimate models will then depend on the availability of the controlling variables, concerning soil, vegetation, climate and land use. For the soil, current programmes to create databases (cartographical inventory and monitoring of quality) will, with the help of specialised supplements, provide a response to needs in the future. In contrast, the information available on land use and changes in land use and practices is insufficient, and new projects must be designed and implemented. The use of spatial remote sensing techniques cannot, alone, produce all the data necessary, but should nonetheless be investigated as it is the most economic means of access to this information.

Establishment of a greenhouse gas emission/sequestration balance and a global environmental account of agricultural practices

These balances need to be drawn up for different farming practices (reduced tillage, green fertilisers and catch crops, integrated production) and also changes in land use (change from crops to grassland). Modelling of their variations is a question of research. Progress will depend on a clearer understanding of mechanisms, and also on acquiring experimental data which remain much too scarce.

Knowledge of the different components in the greenhouse gas or environmental balance should then be integrated in farming and cropping practices, the case of fodder systems justifying special investment because of the strong interactions between plant and animal production in the greenhouse gas budget.

Monitoring of the changes in land use and agricultural production systems

Knowledge of these changes and the technical and economic conditions governing them, is necessary to verify the practices claimed, and also to design and adjust incentive policies. At the level of production systems, the challenge is to develop and maintain databases which are georeferenced and related to different types of farms using these systems. The economic performance of production systems and the behaviour of actors should also be monitored.

Finally, **integrated modelling**, combining the impact of land use changes, climate changes and agricultural and environmental policies, should be developed as an aid to public decision-makers and to inform economic agents.

FOR FURTHER INFORMATION

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GLOSSAIRE

Annex I: Annex to the UNFCCC which lists the countries or groups of countries (Parties) which have subscribed to quantitative framework commitments on greenhouse gas emissions. These are countries which were OECD members in 1992, member states in the European Union and 11 countries moving towards a market economy.

Arable crops: Cereals, oil seeds and protein-rich legumes.

Baseline: Reference situation from which changes in greenhouse gas emissions are measured, resulting from a project or scenario reducing these emissions.

CAP: Common Agricultural Policy (in French: PAC).

Carbon accumulation: Uptake (temporary and reversible) of carbon in an organic form.

Carbon sink: Ecosystem which accumulates more CO_2 than it releases.

Carbon source: Ecosystem which emits more CO_2 than it accumulates, or human activity emitting CO_2.

Catch crop: Crop grown between rows of a crop of a different species.

Certified Emission Reduction (CER) credits: Quotas for the emission of greenhouse gases which can be exchanged between countries and which allow countries subject to emission quotas to comply with them by purchasing additional credits from other countries.

CO_2 Equivalent: Common unit which can be used to express quantities of greenhouse gases: equivalence is defined based on the Global Warming Potential* of different gases.

Conference of the Parties (CoP): Supreme body of the UNFCCC which brings together signatory countries, usually once a year, to assess the progress of the Convention and propose amendments: it is both an institutional body and a forum for discussion and negotiation. The First Conference of the Parties took place in 1995.

Corine Land Cover: Land use database covering the whole of Europe, built up by exploiting remote sensing data (magnification 250x250 m).

Direct drilling: Sowing without prior tillage of the soil.

ECT: Equivalent Carbon Ton.

Exogenous organic matter (EOM): Organic matter put into the soil but not arising from vegetation in situ. Includes animal waste and waste of urban and industrial origin.

Externalities (or extreme effects): Positive or negative influences, intentional or not, exerted by an agent with respect to other agents, without this benefit or harm being the subject of an evaluation by the market or, consequently, of spontaneous monetary compensation.

Farming practice: Technical procedures or cropping operations implemented on a plot.

Georeferencing of data: Recording of its geographical coordinates enabling its spatial localisation. Allows identification of surfaces concerned by a particular use, and the monitoring of their development.

GIEC: Groupe d'Experts Intergouvernemental sur l'Evolution du Climat (in English: IPCC).

Global Warming Potential (GWP) : Parameter allowing evaluation of the relative importance of different greenhouse gases: ratio between the warming effect of a gas and that of C02, taking account of the time during which this gas remains active in the atmosphere.

Green fertiliser: Crop usually sown between two major crops which is then buried in the soil.

Greenhouse effect: Warming of the atmosphere and surface of the Earth caused by certain gases (greenhouse gases) which absorb the thermal infrared rays emitted by Earth and reflect them partially towards the ground. This effect is a natural phenomenon, but it is reinforced by anthropogenic emissions of greenhouse gases.

Greenhouse gas: Gas which partially absorbs long wavelength rays (infrared) emitted by the Earth's surface and by clouds, which heat the lower levels of the atmosphere. The principal greenhouse bases are: water vapour (H_2O), carbon dioxide (CO_2), nitrogen oxide or nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons (CFC), hydrofluorocarbons (HFC), perfluorochemicals (PFC), sulphur hexafluoride (SF6) and ozone (O3).

INRA: National Institute for Agricultural Research.
Intergovernmental Panel on Climate Change (IPCC): A group founded in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to evaluate the data available on evolutions in the climate and the greenhouse effect, and to supply advice for CoP. It can call upon help from some 2500 experts (in French: GIEC).

Intermediate crop: Plant cover between two successive crops so as to avoid leaving the soil bare during the intercropping period.

Kyoto Protocol: UNFCCC Protocol adopted in Kyoto in 1997: an international agreement on reducing emissions of greenhouse gases which fixes quantified commitments (in CO_2 equivalents) to combat global warming. It will not become regulatory until it has been signed by 55% of the countries listed in Annex 1, representing at least 55% of the total emissions in these countries.

Land Management Contract (LMC) (in French, CTE): French system of aid to farmers, with environmental and socioeconomic objectives (French implementation of the 2nd principle of the CAP).

Livestock Unit (LU): Corresponds to a theoretical animal with energy needs of 3000 fodder units (in French: UGB).

LUCAS: Multidisciplinary simulation and modelling tool ("Land Use Change and Analysis System") to evaluate decisions in terms of land use.

LULUCF: Land Use, Land Use Change and Forestry (in French : UTCF).

Maize silage: Maize for fodder stored in silos (lactic acid fermentation).

MEDD: Ministère de l'Ecologie et du Développement Durable (French Ministry for Ecology and Sustainable Development).

MIES : Mission Interministérielle de l'Effet de Serre (French Interministerial Mission on the Greenhouse Effect).

NFI: National Forestry Inventory (IFN).

PG : Permanent grassland.

RGA : Recensement Général de l'Agriculture (French General Census on Agriculture).

Rhizodeposition: Release of organic matter by roots: exudation of organic components, exfoliation of dead cells.

RMQS : Réseau de Mesures de la Qualité des Sols (French Network for Soil Quality Measurements). A measurement and observation network of about 2100 points spread throughout France, providing monitoring (every 5 years) of quantitative data on the state of soils in France.

SAU: Surface Agricole Utile (Useful Agricultural Surface).

Sequestration of greenhouse gases: Applied to greenhouse gases, the opposite of emission. Reference is made to CO_2 sequestration but to carbon accumulation (in the form of organic matter) in the soil.
Soil organic matter (OM): decaying remains of all plants and animals.

STH : Surface Toujours en Herbe (area under permanent grass).

TERUTI : Annual statistical survey performed by the French Ministry of Agriculture on the use and occupation of land (550,000 observation points spread over France on a regular grid).

TG: Temporary grassland.

Trophic network: All food chains linking organisms in a biocenosis.

UNFCCC: United Nations Framework Convention on Climate Change (in French: CCNUCC).

UTCF: Utilisation des Terres, Changements d'affectation des terres et Foresterie (in English: LULUCF).

Waste: Liquid residue, containing solid matter or not, arising from industrial, agricultural or domestic activities.

Win-win: Hypothesis according to which strategies to increase carbon accumulation will also always bring other environmental benefits.

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