A marginal abatement cost curve for climate change mitigation by additional carbon storage in French agricultural land

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Highlights :

Additional carbon storage, net GHG budget, and cost of 8 agricultural practices

MACC shows abatement potential of 39-59 $MtCO_2e.yr^{-1}$ for carbon price 55-250 €.tCO_2e^{-1}

Key practices: agroforestry, hedges, cover crops, grasslands in crop sequences

No “one size fits all strategy” due to heterogeneity across regions and practices

French agricultural carbon sink is 5 times higher than carbon neutrality target

Abstract

Following the Paris agreement at COP21, the European Union (EU) set a carbon neutrality objective by 2050, and so did France. The French agricultural sector can contribute as a carbon sink through carbon storage in biomass and soil, in addition to reducing GHG emissions. The objective of this study is to quantitatively assess the additional storage potential and cost of a set of eight carbon-storing practices. The impacts of these practices on soil organic carbon storage and crop production are assessed at a very fine spatial scale, using crop and grassland models. The associated area base, GHG budget, and implementation costs are assessed and aggregated at the region level. The economic model BANCO uses this information to derive the marginal abatement cost curve for France and identify the combination of carbon storing practices that minimizes the total cost of achieving a given national net GHG mitigation target. We find that a substantial amount of carbon, 36 to 53,5 $MtCO_2e$ yr^{-1}, can be stored in soil and biomass for reasonable carbon prices of 55 and 250 € tCO_2e^{-1}, respectively (corresponding to current and 2030 French carbon value for climate action), mainly by developing agroforestry and hedges, generalising cover crops, and introducing or extending temporary grasslands in crop sequences. This finding questions the 3-5 times lower target retained for the agricultural

carbon sink by the French climate neutrality strategy. Overall, this would decrease French GHG emissions by 8 to 11,7% respectively.

Key words: soil organic carbon sequestration, climate change mitigation, greenhouse gas, carbon neutrality, agriculture, abatement cost

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) demonstrated that in order to keep global warming below +1.5°C compared to the pre-industrial period, it would be necessary to achieve global carbon neutrality by 2050 (Allen et al., 2019). Achieving carbon neutrality implies both drastically reducing greenhouse gas emissions and increasing the terrestrial CO_2 sink, through changes in land use and agricultural and forestry practices that promote carbon sequestration in soils and woody biomass. The EU targets to balance 500-600 $MtCO_2e.yr^{-1}$ of residual emissions with carbon sequestration, 50-85% of which is expected to come from soils and biomass (European Commission, 2018). France is planning to rely even more on biological carbon sequestration, which is expected to offset 80% of its residual 80 $MtCO_2e.yr^{-1}$ in 2050 (MTES, 2020). However, in this planning exercise, the role of agricultural soils is modest – storing 10 $MtCO_2e.yr^{-1}$ – putting a heavy and likely unrealistic pressure on the forestry sector (I4CE, in prep). A thorough assessment of the carbon storage potential of agricultural soils, via the implementation of climate smart practices, and of the related costs is therefore needed in order to design realistic pathways towards carbon neutrality in 2050, both at French and European levels.

Several studies have estimated the cost efficiency of carbon storage practices. Most of these studies focused on no-till or reduced tillage (De Cara et al., 2006, Pautsch et al. 2001, Feng et al. 2000, 2002, 2006 and Kurkalova et al. 2006; Moran et al., 2011, Frank et al., 2015), which have recently been demonstrated to have little to no effect on soil organic carbon (SOC) in temperate regions when the entire soil profile is considered (Haddaway et al., 2017). Other studies have estimated the cost of storing more SOC by introducing temporary grasslands or alfalfa in typical Australian farms (Kragt et al., 2012), converting arable land to permanent grasslands in some US states (Antle et al., 2001), or reducing summer fallow and increasing adoption of conservation tillage in US wheat and corn systems (Antle et al., 2007).

The existing literature presents two shortfalls. First, in most cases, previous studies focus on a single practice, thus falling short of providing an estimate of the total SOC storage potential at regional or national scale. Second, they often neglect to estimate the total GHG budget of practices. While carbon storage is a major component of carbon neutrality strategies, promoting practices for which carbon storage is offset by increased GHG emissions would be obviously counter-productive. Moreover, carbon pricing mechanisms such as cap-and-trade systems or carbon offsetting schemes incentivize the total GHG budget, rather than its sub-components. Likewise, some studies have analysed the mitigation potential of some practices that are favourable to carbon storage, such as introduction of cover crops, agroforestry and better grassland management (Pellerin et al. 2017, Fellmann et al. 2021) or land-use change (Mosnier et al. 2019). Nonetheless, these studies fall short of estimating the large-scale potential for carbon storage and rely on rough assumptions for the effects of these practices on carbon storage.

The objectives of this study are to assess the carbon storage potential, the net GHG balance and the cost efficiency of a large range of agricultural practices in order to refine the French and European carbon neutrality strategies.

Marginal Abatement Cost Curves (MACCs) which inform on the costs of an additional unit of emission reduction at any given total abatement level (Huang et al. 2016) provide useful information to develop climate change policies. They help identifying the mitigation measures that should be prioritized to meet climate mitigation targets and assessing the necessary carbon price to reach them. Povellato et al. (2007), Kuik et al. (2009), Vermont and De Cara (2010), Eory et al. (2018) reviewed different approaches used to derive MACCs. Vermont and De Cara (2010) divide them in three broad categories: (i) supply-side, micro-economic models among which are micro-econometric and mathematical programming models, (ii) equilibrium models that simultaneously model supply and demand in one or more sectors of the economy, and (iii) engineering cost approaches. The first two approaches represent the behaviour of economic agents (producers and/or consumers) and typically estimate the mix and the share of adoption of each mitigation practice for a given carbon price. Engineering models generally estimate the cost of mitigation practices one by one and sort them by increasing cost-effectiveness (Pellerin et al., 2017, Eory et al., 2018). Except from Biggar et al. (2013) where results are disaggregated by the main US regions and by crop type, MACCs from engineering models generally aggregate mitigation potential and cost per measure at the national level.

Here we estimate the MACC of all SOC storing practices which are relevant in mainland France. To do so, we use the BANCO model (Bamière et al., 2017) which is in-between supply-side models and engineer-type approaches. The mitigation potential per hectare, costs and maximum area of application of each practice are estimated for each region, based on detailed crop and grassland biophysical simulations or on literature and expert knowledge. An optimization procedure then allows to determine the cost-minimizing allocation of the effort across practices and regions to achieve various climate mitigation targets at national level. We demonstrate that 36 to 53,5 $MtCO_2e.yr^{-1}$ - the equivalent of 8 to 11,7% of current French GHG emissions - can be stored in the soil and biomass of agricultural land for reasonable carbon prices of 55 and 250 €.tCO_2e^{-1}.

2. Methodology

2.1. Selection of SOC storing practices

The SOC storing practices were identified based on a literature review for the three major land-use types: croplands including temporary grasslands, permanent grasslands and forests. Land-use changes between these three types were not considered. Eight carbon storing practices were found relevant for France (Table 1~~Table 1~~): 1) spatial or temporal expansion of cover crops; 2) mobilization of new exogenous organic carbon resources currently not applied on agricultural soils; 3) replacement of silage maize with temporary grasslands; 4) agroforestry; 5) hedges; 6) moderate intensification of extensive grasslands; 7) grassland grazing instead of mowing; and 8) grass cover of vineyards. No/low-tillage practices are excluded in the present study according to the most recent meta-analysis showing that, in the temperate context, no-tillage results in a redistribution of SOC over the soil profile with little to no increase in total SOC when the entire soil profile is considered (Haddaway et al., 2017; Ogle et al., 2019).

These eight practices also happen to be the most relevant for total carbon storage (including biomass) on agricultural land (cropland and grassland). Regarding forest soils, existing scientific evidence only provides one clear recommendation: avoiding whole-tree harvesting – including remnants and stumps (Achat et al., 2015; Mayer et al., 2020). Fortunately, this type of harvesting remains exceptional in France and accordingly, no alternative SOC storing practice was assessed for forest soils. For these two reasons, our estimate covers the total carbon storage, soil and biomass, of agricultural land. For more details on the literature review and selection process, see Pellerin et al. (2020).

	General description	Major additional working operations and investments	Carbon storage potential from literature review	References	Method used to evaluate the carbon storage potential in this study
Expansion of cover crops in croplands	Cover crops temporal extension (0.5-4 months) in areas where cover crops are already planted and cover crops spatial expansion in areas where cover crops are not present	Purchase of seeds, sowing, and mechanical destruction. Irrigation at seeding where needed and possible	313 ± 313 kg C ha^{-1} yr^{-1}	Justes et al. (2013), McDaniel et al. (2014), Poeplau & Don (2015), Lal (2015), Constantin , et al. (2010)	Crop simulations at high spatial resolution with a process-based crop model (STICS)
New organic C inputs in croplands	Application in croplands of compost or digestate from organic waste and sludge from waste water treatment plants, both from sources that are not currently incinerated or buried in landfills.	Purchase, transport and spread of new organic C inputs Reduction of synthetic fertilization	100 kg C ha^{-1} yr^{-1} (sewage sludge), 100 kg C ha^{-1} yr^{-1} (liquid manure), 300 kg C ha^{-1} yr^{-1} (manure), 500 kg C ha^{-1} yr^{-1} (compost)	Zavattaro et al (2017), Morvan et al (2013), Powlson et al (2012)	Crop simulations at high spatial resolution with a process-based crop model (STICS)
Expansion of temporary grasslands in croplands	Extension (1-2 extra years) of existing temporary grasslands in crop rotations and substitution of fodder maize by temporary grasslands in crop rotations.	Reduction of synthetic fertilization Change in animal feed rations Change in crop-specific technical operations	~130 to 500 kg C ha^{-1}.yr^{-1} (first 10 years after the plantation of a grassland)	Conant et al (2001), Franzluebbers et al (2014), Johnston et al (2017), Creme et al (2020)	Crop simulations at high spatial resolution with a process-based crop model (STICS)
Agroforestry in croplands	Plantation of trees *Juglans regia* x *nigra*, *Prunus avium*) in croplands (75 trees/ha).	Tree plantation and maintenance Timber harvest	250 kg C ha^{-1} of UAA.yr^{-1} (-230; +730) in the soil (cropland only) 900 kg C ha^{-1} yr^{-1} (-430; +1350) in the biomass	Cardinael et al (2017), Lorenz & Lal(2014), Kim et al, (2016), De Stefano & Jacobson (2017), Feliciano et al (2018), Cardinael et al (2018), Chatterjee et al (2018), Shi et al (2018), Pardon et al (2017), Drexler et al. (2021)	Assessment based on literature, national resolution
Hedges in croplands	Plantation of trees at the border of croplands (49 to 68 linear m/ha).	Tree plantation and maintenance Timber harvest	750 kg C.ha^{-1} of hedges.yr^{-1} (490; 1020) in the soil (cropland only) 240 kg C .ha^{-1} of UAA.yr^{-1} (-120; +370) in the biomass		Assessment based on literature, national resolution

			(authors' calculations)		
Moderate intensification of extensive grasslands	Increase of synthetic fertilization (here +50 kg $N.ha^{-1}$) in permanent grasslands having a low initial level of synthetic fertilization	Increase use of synthetic fertilizers	0-210 ±70 kg C ha^{-1} yr^{-1}	Conant et al.(2017), Sandermann et al. (2015), Abdalla et al. (2018), Franzluebbers &Stuedemann (2009), Poepleau et al (2018).	Permanent grassland simulations at high spatial resolution with a process-based grassland model (PaSim)
Grazing instead of mowing in permanent grasslands	Substitution of mowing by direct grazing in permanent grasslands whose management is mixed (based on grazing and mowing) Substitution of 1 our 2 cuts per year.	Change in synthetic and organic fertilization Change in harvest operations of hay and silage	From 111 ± 11 to 380 ± 20 kg $C.ha^{-1}$ yr^{-1} depending on biomass removal	Pineiro et al. (2010) ; McSherry & Ritchie, (2013) ; Soussana & Lemaire (2014) ; Lu et al. (2017) ; Zhou et al. (2017) ; Abdalla et al. (2018) ; Eze et al. (2018) ; Byrnes et al. (2018)	Permanent grassland simulations at high spatial resolution with a process-based grassland model (PaSim)
Grass cover of vineyards (winter or permanent cover)	Permanent or winter grass cover of vineyards except for Cognac and Mediterranean vineyards and in stony ground areas	Plantation of grass cover and purchase of seeds Mechanical destruction (winter grass cover) Removal of chemical destruction (permanent grass cover) Increased use of synthetic fertilizers	From 160 (winter) 490 (permanent) kg C ha^{-1} yr^{-1}	Constantin et al. (2012), Arrouays et al. (2002)(2002)	Assessment based on literature, national resolution

Table 1: Key characteristics of the eight carbon storing practices considered in this study

2.2. General assumptions and baseline

The additional carbon storage and cost incurred by the adoption of a storing practice are measured relative to a reference situation, over a 30-years simulation period, assuming constant market context and cropping systems corresponding to the average 2009-2013 period. Climate conditions are also assumed to be the same for all scenarios and correspond to the 1983-2013 period. The land-use shares of croplands, permanent grasslands and forests are assumed to be constant (no land-use changes over time nor between scenarios).

2.3. Additional carbon storage assessment and GHG budget

2.3.1. Carbon storage

One originality of the study lies in its high spatial resolution. The simulations were performed at the scale of 30 966 homogeneous agricultural pedoclimatic units (PCU, size < 8x8km), each one being characterized by its local climate, dominant soil type(s), 1 to 3 dominant cropping and grassland systems (crop/grassland sequences identified in French Land Parcel Identification System and current crop/grassland management practices identified in national surveys), and initial SOC stock from soil inventory data (Mulder et al., 2016) (see Table A 1 for a summary of data sources).

The simulations were carried out using two process-based ecosystem models, STICS (Brisson et al, 2003, pre-version 10) for arable crops and PaSim (Ma et al, 2015, version 5.3) for permanent grasslands. Both models include an explicit representation at a daily time step of the water, nitrogen, and carbon cycles in the soil, plant growth, and account for the effect of the multiple pedoclimatic factors (e.g. radiation, temperature, precipitation, detailed soil properties) and management practices that drive these processes. They both provide multiple outputs including crop and grass production, change in SOC stock, nitrogen leaching, and GHG emissions (NH_3 and N_2O emissions, enteric CH_4). PaSim simulates the SOC dynamics over the whole soil depth while STICS consider it only for the first 30 cm. To estimate carbon storage over the entire soil profile (0-100 cm), STICS results for the first 30 cm were extrapolated using the function proposed by Balesdent et al (2018) (Table A 3). Details regarding the modelling approach are provided in Graux et al., (2020), Launay et al., (2021a) and the simulation outputs are accessible online (Launay et al., 2021; Martin, 2021).

In order to minimize modelling bias, we focus on the additional carbon storage, calculated as the difference between the simulated C stock under C storing practices and the simulated C stock under current management practices (i.e. baseline), after a 30 years period:

additional C storage (tC ha-1 yr-1) = $\frac{(final\ C\ stockstoring\ practice - final\ C\ stock\ baseline)}{simulation\ le\quad in\ years}$

Current soil-crop models are not able to simulate the carbon stock changes resulting from agroforestry, hedges and grass cover of vineyards. The average value for additional storage from the literature review (cf. Table 1~~Table 1~~) was retained for these three practices, without considering spatial heterogeneity.

2.3.2. Greenhouse gases budget

For each storing practice, a complete GHG budget was also calculated. Carbon sequestration in soil and biomass, N_2O emissions, nitrate leaching, and NH_3 volatilization were simulated by STICS and PaSim for croplands and grasslands, respectively. The emissions associated to changes in fertilizer manufacturing, fuel consumption and substitution of carbon-intense materials and energy by wood use were also estimated.

We assumed that farmers buy or sell the differences of fodder induced by the new practice, thus maintaining both animal feed and animal production levels. Consequently, there is no variation in enteric methane and manure management emissions.

The detailed values and sources of emission factors are available in Bamière et al. (2021).

2.4. Implementation cost assessment

Implementation costs are calculated as the difference between the storing practice and the current practice. A negative cost represents a gain for the farmer. We account for overhead variations (purchase of inputs, crop management operations impacting labour, machinery or fuel, etc.), dedicated investments, and revenue changes associated with production changes (yield variation, change in land allocation - e.g. crop area substituted with trees or hedges, wood sales, etc.), excluding any "optional subsidy" (e.g. Common Agricultural Policy payments, agri-environmental measures, local subsidies). For the storing practices implying cash flows varying over time (agroforestry and hedges), we compute a constant annuity with a 4.5% discount rate (Quinet et al. (2013)).

The technical changes resulting from the implementation of storing practices (e.g. changes in input and labour use, land allocation, …) are derived from the literature or, when not available, from expert knowledge. All technical changes and the corresponding sources of information are documented in Bamière et al. (2021).

In order to minimize modelling bias, simulated yields were used to estimate variation coefficients that were applied in percentage to the reference yield of each crop obtained from national statistics. Absolute simulated yields were only used for grass due to the lack of national statistics on grass yield. In addition, crop species which are not explicitly simulated by STICS are assumed to undergo the same yield and inputs variations as the most similar simulated crop (for example, durum wheat, is associated with winter wheat).

Gross margin losses resulting from changes in land allocation (e.g. agroforestry tree line footprint) are estimated based on data from the Farm Accountancy Data Network (FADN). When the changes in land allocation are crop-specific (e.g. substitution of fodder maize with grass, which can in turn change the share of other crops such as soft wheat or rapeseed in a crop sequence), we use crop-specific gross margins. The gross margins per crop are not directly available in the French FADN. Prices and yields are available for each crop, but input costs (e.g. seeds, fertilizer, ...) are only reported at the farm level. We therefore estimate crop-specific costs using a linear regression on the farms' land allocation to distribute the expenses among crops. This work is carried out in each of the regions. When, for a given crop, the estimates are not significantly different from zero at a 5% level (or if the sample size is lower than 30 farms), we use the gross margin of the same crop in a neighbouring region or, if not available, the one estimated at the national level. Because a large part of fodder crops is self-consumed, yield and/or prices for alfalfa, grass and fodder maize are not available in FADN data and were obtained from annual agricultural statistics (Table A 1).

Any yield variation specific to fodder is assumed to be compensated by a substitute feed ration with the same energy and protein level and with a similar fill value, resulting in unchanged milk and meat production. Feed purchases or sales are adjusted accordingly.

2.5. ***Area base of carbon storing practices and aggregation of results at the region level***

Technical criteria on the applicability of a given storing practice are derived from the literature and, when not available, from expert knowledge (Table A 2). They are used to quantify the maximum potential area base of each selected practice. These criteria can lead to the exclusion of certain crops, crop sequences, or soil types for a given storing practice (e.g. no cover-crop for intercropping period <2 months, no agroforestry if soil depth <1m or plot size <1ha).

STICS and PaSim only simulate the dominant cropping/grassland systems in each pedo-climatic unit (PCU). In order to ensure the representativeness of the results at regional and national levels, a three-stage spatial aggregation procedure is implemented. First, of the area of each "dominant cropping system" is upscaled so that the area simulated by the models equals the agricultural area of the whole PCU. Then, knowing the weight of each PCU in the region, an aggregation is carried out at the regional level. Finally, a crop-specific correction factor is applied to match the regional areas of each crop from the Annual Agricultural Statistics.

Area bases, regional costs, and regional additional storage potentials of each practice are provided in Table A4 to A7.

2.6. *Cost-effective allocation of the additional carbon storage effort*

In the context of climate change mitigation, rewarding carbon storage regardless of the GHG budget of practices makes little sense. The cost-effective allocation of the net GHG abatement (net GHG mitigation plus additional carbon storage) effort across practices and regions is therefore determined, based on the per hectare cost for farmer and net GHG budget, as well as the potential applicability of each practice in each region.

For that purpose, we use the BANCO model (Bamière et al, 2017), which optimizes the uptake level ($\sum_c X_{r,p,c}$, in ha) for each practice *p* in each region *r*, to minimize the total mitigation cost to achieve a national mitigation target, considering compatibility constraints between practices (e.g. for agroforestry, tree rows are no more available for other SOC storing practices). The total cost TC (Eq.1) and the total mitigation are determined by the sum for all regions (r), practices (p), and crops (c) of the actual uptake level of the measure ($X_{r,p,c}$) times the associated unitary costs ($uc_{r,p,c}$) and unitary abatement ($ua_{r,p,c}$), respectively. The constraints are: (i) compliance with a total mitigation target TM (Eq.2), (ii) compliance with the maximum area base ($\overline{X_{r,p,c}}$) for each tuple (region, practice, crop) (Eq.3), and (iii) competition between measures for the use of land at the region level (Eq.4). Equation 4 reads as, for instance, the total number of hectares of a given crop *c* used by mutually exclusive practices ($I_{p,p',c} = 1$) in a given region must not exceed the total initial area of crop *c* in this region ($\overline{X_{r,c}}$), minus the area of crop *c* converted to another land use ($X_{r,p',c} * luc_{r,p',c}$, $luc_{r,p',c}$ being the land use conversion coefficient). For example, the wheat area concerned by cover cropping plus the wheat area converted to tree rows due to agroforestry or hedges implementation, must not exceed the total wheat area of the region (based on national statistics).

The crop index is a modelling proxy for crop sequences, in order to accurately account for the actual uptake potential of practices, because some practices are not applicable to all crop sequence (e.g. cover crops can sometimes be implanted after wheat and sometimes not, depending on the sowing date of the following crop) or to the whole area of a given crop sequence (e.g. minimum soil depth of 1m for agroforestry). However, results are only presented at the practice x region grain because storing practices cannot in practice be implemented on a single crop.

Net emitting practices in a given region are also excluded from the cost-effective allocation of the mitigation effort.

$$\min_{X_{r,p,c}} TC = \sum_{r,,p,c} uc_{r,p,c} \times X_{r,p,c} \qquad \text{Eq. 1}$$

$$\text{s.t.} \quad \sum_{r,p,c} ua_{r,p,c} \times X_{r,p,c} = TM \ , \ \ (\lambda) \qquad \text{Eq.2}$$

$$0 < X_{r,p,c} \ \leq \ \overline{X_{r,p,c}} \ , \ \forall (r,p,c) \qquad \text{Eq.3}$$

$$\sum_{p' \geq p} \left(X_{r,p',c} * I_{p,p',c} * luc_{r,p',c} \right) \leq \overline{X_{r,c}}, \ \ \forall (r,p,c) \qquad \text{Eq.4}$$

By varying the national mitigation target and reporting the associated marginal cost (λ in €.tCO_2e^{-1}, dual price of Eq.2), we are able to depict a marginal abatement cost curve.

The model is written in GAMS, non-linear programming and solved with the CONOPT solver.

3. Results

3.1. Cost and efficiency per storing practice

SOC storage represents the bulk of the net GHG budget for most practices (Table 2~~Table 2~~, Table 3~~Table 3~~). The three exceptions are agroforestry and hedges, for which biomass storage is the most important component, and the moderate intensification of permanent grasslands, for which the increase in fertilisation and related N_2O emissions cancels out the benefits of SOC storage. The practices with the highest potential for additional SOC storage per hectare ($tCO_2e.ha^{-1}.yr^{-1}$) are agroforestry, grass cover of vineyards, and the replacement of mowing by grazing, with more than 1 $tCO_2e.ha^{-1}.yr^{-1}$. They are followed by the expansion of temporary grasslands and cover crops and the moderate intensification of extensive grasslands, with circa 0.75 to 0.80 $tCO_2e.ha^{-1}.yr^{-1}$, and finally new organic C inputs in cropping systems and hedges.

On the whole, additional carbon storage is costly to farmers. Four practices, grass cover of vineyards, new organic resources, moderate intensification of permanent grasslands, and cover crops expansion, have moderate average implementation costs (from -26 to 39 €.ha^{-1} on average at the national level, see Table 3~~Table 3~~). They are dominated by additional input or machinery costs (e.g. mineral N fertilizer in grasslands, seeds and sowing of the cover crops, purchase and delivery of green waste compost), which are only partly compensated for by an increase in production (e.g. increased grass yield, increase in yield for some crops in the case of cover crops, slight increase or stabilisation of yields over time for the new organic resources).

Practices such as grazing instead of mowing, the expansion of temporary grasslands in crop rotations, agroforestry, and hedges have higher average implementation costs (73 to 118 €.ha^{-1}, see Table 2~~Table 2~~). The last three practices all imply some crop substitution, thus decreasing the share of cash crops. The resulting loss of revenue is neither compensated for by wood sales (agroforestry and hedges), nor by inputs or machinery savings (temporary grasslands). As for the substitution of mowing by grazing, it implies a decrease in hay and grass silage stocks, the cost of which generally not being offset by the increase in grazed fodder nor by the savings in harvesting costs.

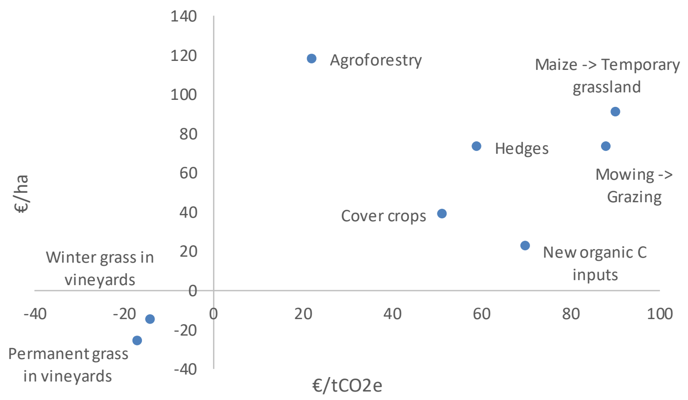

Figure 1 National average implementation costs of practices carbon storing, in relation to their abatement cost (based on net GHG budget).

What matters more for decision makers is the cost-efficiency of the various storing practices. Overall, abatement costs per tCO_2e are correlated with implementation costs per hectare (Figure 1~~Figure 1~~). However, agroforestry and hedges are among the most expensive practices per hectare, but become the second and fourth cheapest respectively on a per tCO_2e basis, thanks to their storage potential (mostly woody biomass). To the contrary, the merit of new organic resources is greatly diminished. In the end, the most cost-efficient practices are (on average at the national level) grass cover of vineyards, agroforestry, cover crops, and hedges. Their abatement costs per tCO_2e are lower than or close to the current French carbon target value[1]

[1] Value that serves as a benchmark for evaluating public investment projects in France. It gives the threshold below which we consider that the implementation of a storing practice is beneficial for society as a whole, without prejudging the public policy instrument to be implemented. The Value for Climate Action (strategie.gouv.fr)

(i.e. 55€.tCO_2e^{-1}). Nevertheless, after excluding the practices that were net emitters in some regions, nearly all C storing practices in the remaining regions have an abatement cost that fits below the carbon target price set by France to achieve carbon neutrality by 2050 (i.e. 250 €.tCO_2e^{-1}, Quinet et al. (2019)).

As we can see in Table 2~~Table 2~~, there is great inter-regional variability in the cost-efficiency of SOC storing practices, arising from the regional implementation cost and/or net abatement potential per hectare. This heterogeneity is mainly due to the heterogeneity of land allocation, yield potential, and cropping and grassland systems between the different agricultural production basins, as well as the yield variation level following the uptake of a practice. Some regions in northern France are important producers of high gross margin crops such as sugar beets and potatoes. Practices that lead to a decrease in cultivated land, such as agroforestry, hedges, and introduction of temporary grasslands in crop sequences are then particularly costly in these regions.

Extending the duration of existing cover crops is cheaper than introducing them in crop sequences, making the cover crops lever cheaper in regions where extending duration is more often feasible. The cost of introducing cover crops also increases with the share of grain maize which requires the use of more expensive cover crops seeds such as faba beans and vetches, and also often leads to an increase in irrigation (see Launay et al., 2021). These additional expenses are not always offset by an increase in production.

The regional variability of the new organic C inputs implementation cost depends mostly on the type of organic resources available in the region (purchase price, delivery and spreading costs): digestates and sludge composts from wastewater treatment plants are currently nearly costless for farmers, unlike bio- and green-waste composts.

Finally, the heterogeneity in crop and grassland systems and in pedo-climatic conditions across regions also influences the potential for additional SOC storage and the net GHG budget of the various practices (see Launay et al, 2021, for a comprehensive discussion).

*Table 2 National average results per storing practice (in bold). Regional extrema are provided in brackets. Average additional SOC storage is reported for the whole soil profile (0-100 cm). The net GHG budget includes additional C storage in soil and biomass and other GHGs mitigation. A negative/positive GHG budget corresponds to a net carbon sequestration/ a net emission, respectively. (*Excluding net emitting regions)*

Storing practices	Potential applicability	Additional SOC storage	Net GHG budget	Cost for farmer	SOC storage cost	Abatement cost
	(Mha)	(tCO$_2$e ha^{-1} yr^{-1})	(tCO$_2$e ha^{-1} yr^{-1})	(€ ha^{-1} yr^{-1})	(€ tCO$_2$e^{-1})	(€ tCO$_2$e^{-1})
Expansion of cover crops	**16,03**	**-0,775** (-1,392; -0,148)	**-0,736** (-1,340;-0,141)	**39** (12; 147)	**49** (19; 301)	**51** (20,3; 304,9)
New organic C inputs	**1,46**	**-0,359** (-0,722; -0,066)	**-0,324** (-0,668;-0,111)	**22,6** (-92; 269)	**63** (-127; 933)	**70** (-137,7; 1 195,9)
Expansion of temporary grasslands	**6,63**	**-0,785** (-2,747;0,010)	**-0,903** (-3,014;-0,087)	**91** (-41; 314)	**116** (-66; 455)	**90** (-47,8; 269,7)
Agroforestry	**5,33**	**-1,432** (-1,718; -0,706)	**-5,306** (-5,629;-4,493)	**118** (63; 179)	**82** (53; 105)	**22** (12,7; 32,0)
Hedges	**8,83**	**-0,115** (-0,144; -0,056)	**-1,236** (-1,385;-0,974)	**73** (54; 87)	**633** (549; 987)	**59** (52,8; 65,9)
Moderate intensification of extensive grasslands	**3,94**	**-0,747** (-1,118; -0,116)	**0,010** (-0,326;1,131)	**28** (12; 38)	**35** (16;324)	**101** (49,3; 136,1) *
Grazing instead of mowing (perm. grass.)	**0,09**	**-1,349** (-1,962; -0,111)	**-0,986** (-1,149;-0,173)	**73** (-85; 146)	**55** (-761; 141)	**88** (-491,0; 293,3)
Grass cover of vineyards permanent	**0,15**	**-1,704** (-2,212; -1,301)	**-1,534** (-1,892;-1,256)	**-26** (-27; -22)	**-15** (-21; -11)	**-17** (-21,8; -13,4)
in winter	**0,41**	**-1,100** (-1,100; -1,100)	**-1,087** (-1,087;-1,087)	**-15** (-15; -15)	**-14** (-14)	**-14** (-14,0; -14,0)

Table 3: Detail of the net GHG mitigation potential of each storing practice. The national average results per practice are in bold, the regional extrema are provided in brackets. Average additional SOC storage is reported for the whole soil profile (up to 1 m). A negative/positive GHG budget corresponds to a net carbon sequestration/ a net emission, respectively.

Storing practices		**Potential applicability**	**Additional SOC storage**	**Biomass C storage**	**Other GHGs**	**Net GHG budget**	**Total additional SOC storage potential**	**Total abatement potential**
		(Mha)	($tCO_2e\ ha^{-1}\ yr^{-1}$)	($tCO_2e\ ha^{-1}\ yr^{-1}$)	($tCO_2e\ ha^{-1}\ yr^{-1}$)	($tCO_2e\ ha^{-1}\ yr^{-1}$)	($M\ tCO_2e\ yr^{-1}$)	$MtCO_2e\ yr^{-1}$
Expansion of cover crops		**16,03**	**-0,775** (-1,392; -0,148)	**0,000**	**0,023** (-0,005;0,089)	**-0,736**	12,43	-12,06
New organic C inputs		**1,46**	**-0,359** (-0,722; -0,066)	**0,000**	**0,035** (-0,045;0,104)	**-0,324**	0,53	-0,47
Expansion of temporary grasslands		**6,63**	**-0,785** (-2,747;0,010)	**0,000**	**-0,219** (-0,484; -0,097)	**-0,903**	5,21	-6,66
Agroforestry		**5,33**	**-1,432** (-1,718; -0,706)	**-3,300**	**-0,574** (-0,616; -0,485)	**-5,306**	7,63	-28,26
Hedges		**8,83**	**-0,115** (-0,144; -0,056)	**-0,893** (-0,995; -0,716)	**-0,228** (-0,247; -0,203)	**-1,236**	1,02	-10,91
Moderate intensification of extensive grasslands		**3,94**	**-0,747** (-1,118; -0,116)	**0,000**	**0,784** (-1,118; -0,116)	**0,010**	2,95	0,15
Grazing instead of mowing (perm. grass.)		**0,09**	**-1,349** (-1,962; -0,111)	**0,000**	**0,517** (-0,061;0,961)	**-0,986**	0,12	-0,7
Grass cover of vineyards	permanent	**0,15**	**-1,704** (-2,212; -1,301)	**0,000**	**-1,100** (0,046;0,320)	**-1,534**	0,26	-0,23
	in winter	**0,41**	**-1,100** (-1,100; -1,100)	0,000	**0,013** (0,013;0,013)	**-1,087**	0,45	-0,45

3.2. Maximum storage potential

Assuming the additivity of our eight practices, the maximum cumulated technical potential for carbon storage in soil and biomass amounts to 56 MtCO2e.yr^{-1} at the national level, of which 30.6 MtCO2e.yr^{-1} are in the soil. 98% of this storage potential comes from five practices: the expansion of cover crops and temporary grasslands and the moderate intensification of permanent grasslands, thanks to their large area base, and agroforestry and hedges, which also benefit from a high storage potential per hectare. The maximum cumulated technical abatement potential is 59 MtCO2e.yr^{-1}.

Now, accounting for interactions between practices and the cost-effective allocation of the net GHG abatement effort, the maximum economic abatement potential is 58,9 MtCO2e.yr^{-1}, corresponding to 77% and 13% of the agricultural and the national GHG emissions, respectively. This net GHG abatement arises at 91% from additional carbon storage in soil (28.2 MtCO2e.yr^{-1}) and in biomass (25,5 MtCO2e.yr^{-1}) (see Figure 3~~Figure 3~~ and *Table 4~~Table 4~~*). Four practices account for 97% of the net abatement: agroforestry (48%), hedges (18,5%), the expansion of cover crops (19.6%), and, to a lesser extent, the expansion of temporary grasslands (11%).

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Mis en forme : Police :11 pt, Couleur de police :

3.3. Marginal abatement cost curve

The marginal abatement cost curve depicted by means of the cost-effective allocation model BANCO is analysed at four interesting points: (A) with no incentive to store carbon in soils; for the current (B) and 2030 (C) carbon target price set by the French government; and (D) the maximum abatement (Figure 2~~Figure 2~~).

Mis en forme : Police :11 pt, Non Italique, Couleur de police : Automatique

Scenario	(A) No incentive	(B) 55 € tCO2e-1	(C) 250 € tCO2e-1	(D) Maximum abatement
Total net GHG abatement (M tCO$_2$e yr^{-1})	1,08	39,52	58,72	58,90
of which (in %)				
additional soil carbon storage	98%	47%	48%	48%
additional carbon sequestration in biomass	0%	45%	43%	43%
other GHG abatement	2%	8%	9%	9%
Total cost to farmers (M€ yr^{-1})	-45,9	900,5	2452,9	2538
Marginal abatement cost (€ tCO$_2$e^{-1})	-4,66	54,4	249	1 328
Storing practices contribution (M tCO$_2$e yr^{-1}) :				
Expansion of cover crops	0,000	8,137	11,432	11,526
New organic C inputs	0,176	0,280	0,441	0,474
Expansion of temporary grasslands	0,162	1,836	6,455	6,484
Agroforestry	0	28,259	28,259	28,259
Hedges	0	0,213	11	10,913
Moderate intensification of extensive grasslands	0	0,053	0,349	0,349
Grazing instead of mowing permanent grasslands	0,020	0,020	0,071	0,073
Grass cover of vineyards (permanent)	0,233	0,233	0,233	0,233
Grass cover of vineyards (winter)	0,448	0,448	0,448	0,448

Table 4: Total net GHG abatement, total cost to farmers, marginal abatement cost, and contribution of the storing practices at (six) points of the marginal abatement cost curve.

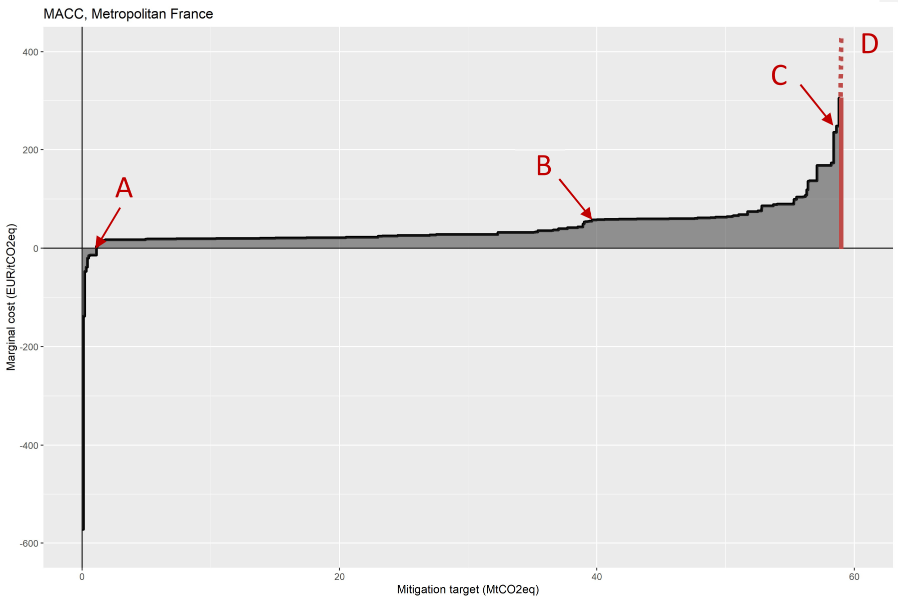

Figure 2: Marginal abatement cost curve for mainland France: net GHG abatement (MtCO2e yr-1) on X axis; marginal abatement cost (€ tCO2e-1) on Y axis.

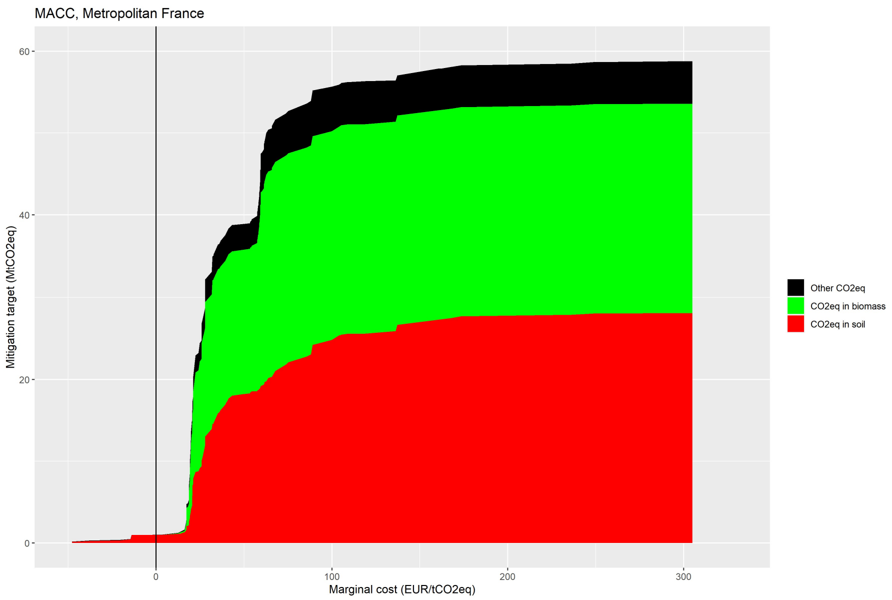

Figure 3 : Marginal abatement cost curve: contribution of SOC carbon storage, biomass C storage, and other GHGs to the total abatement target (Y axis), depending on the marginal abatement cost (€ tCO2e-1, on X axis).

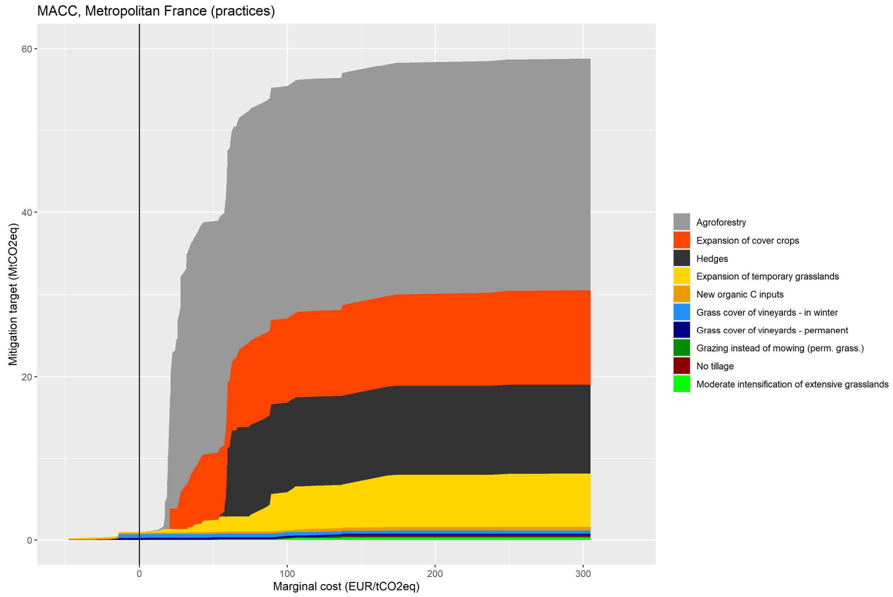

Figure 4: Marginal abatement cost curve: contribution of SOC storing practices to the total abatement target (Y axis), depending on the marginal abatement cost (€ tCO2e-1, on X axis).

The maximum abatement potential is obtained for a total cost for farmers of 2 538 M€.year^{-1} and a marginal cost (i.e. the cost of the last ton of CO_2e abated) of 1 328 € tCO_2e^{-1}, which is far more expensive than the current (55 €.tCO_2e^{-1}) and the 2030 (250 €.tCO_2e^{-1}) target carbon prices.

For a cost of carbon varying from 55 to 250 € tCO_2e^{-1}, it is possible to avoid the emission of 39,5 to 58,7 MtCO_2e.yr^{-1}. The associated additional carbon storage in soil and biomass amounts to 36,3 to 53,2 MtCO_2e.yr^{-1}, including 18,6 to 28,1 MtCO_2e.yr^{-1} for the sole additional SOC storage (Figure 3~~Figure 3~~). And the total cost for farmers would range from 900 to 2 453 M€.yr^{-1}.

As for the practices to be deployed at the national level, agroforestry and cover crops are essential whatever the net mitigation target and the carbon price (Figure 4~~Figure 4~~). The

Mis en forme : Police :11 pt, Non Italique, Couleur de police : Automatique

Mis en forme : Police :11 pt, Non Italique, Couleur de police : Automatique expansion of temporary grasslands has a wide abatement cost range depending on the regional context and the practice is deployed progressively. Hedges become essential only for high national mitigation targets.

The regional breakdown of the national mitigation target shows that there is no "one-size-fits-all" solution, but rather a combination of good practices at the right place (Figure 5~~Figure 5~~ and 6). For a given mitigation target (or carbon price), the contribution of each region varies both in absolute value and in composition (i.e. type of practice implemented). Our results thus provide useful information for the design of cost-effective policies at the region level, among which the territorial climate-air-energy plans that the regions have to set up.

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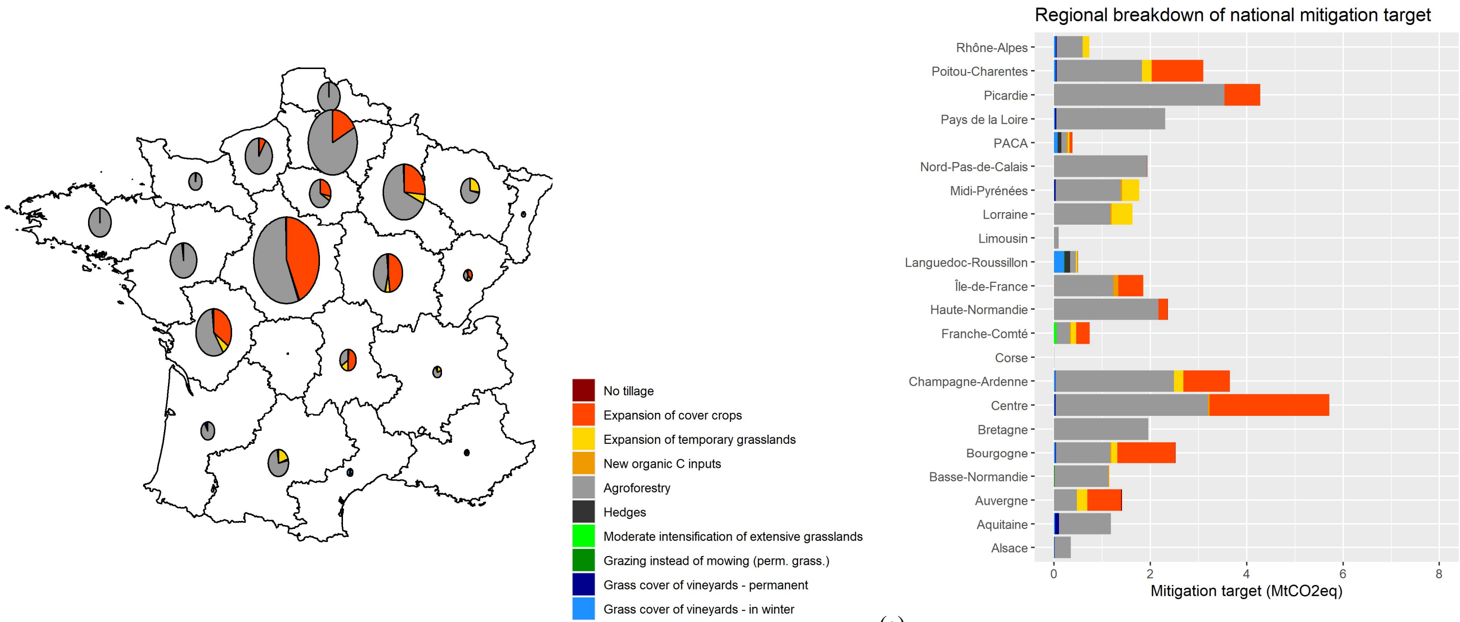
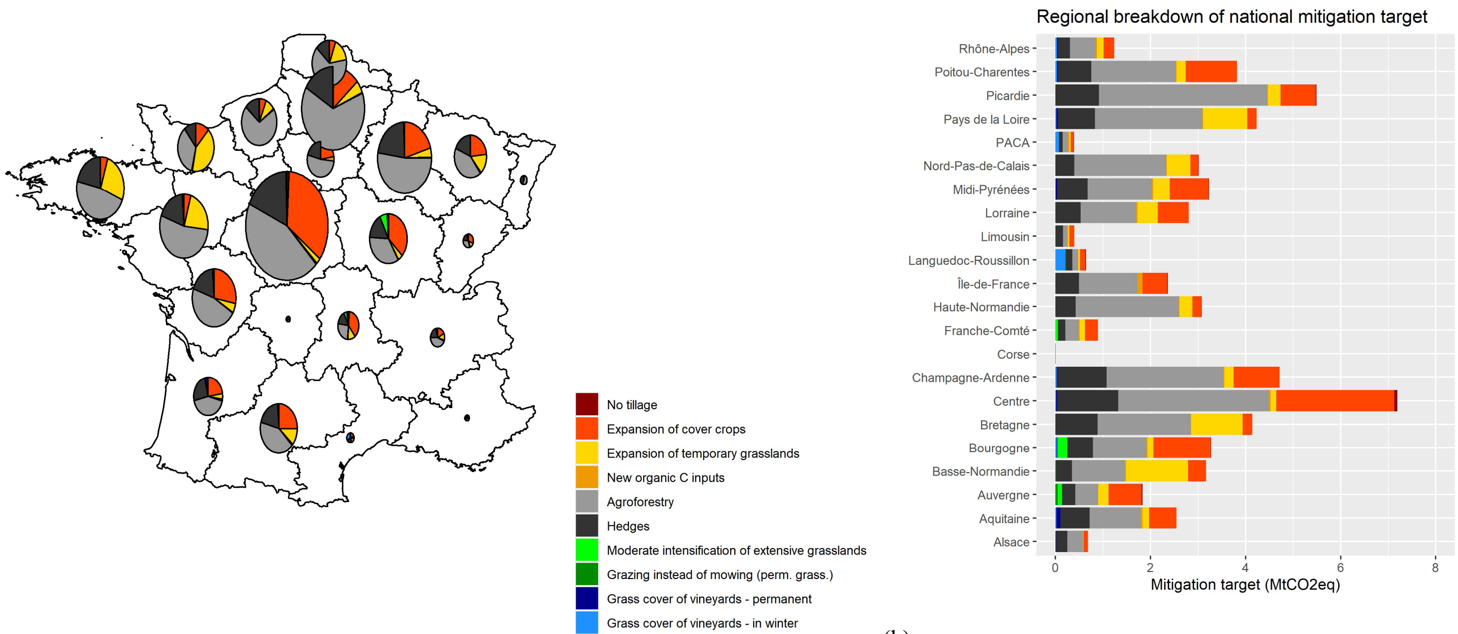
Mis en forme : Police :(Par défaut) Times New Roman, 12 pt, Non Italique, Couleur de police : Automatique, Vérifier l'orthographe et la grammaire



(a)

Figure 5 : Regional carbon storage allocation, in MtC yr^{-1}, detailed per storing practice for the current (201,7 € tC^{-1} or 55€ tCO$_2$e^{-1}) target carbon price (i.e. value for climate action) in France.



(b)

Figure 6 : Regional carbon storage allocation, in MtC yr^{-1}, detailed per storing practice for the 2030 (b: 917 € tC^{-1} or 250€ tCO$_2$e^{-1}) target carbon price (i.e. value for climate action) in France.

4. Discussion

4.1. Comparison with previous studies

Our results show an overall net GHG abatement potential of 58,7 $MtCO_2e.yr^{-1}$ at a cost lower than 250 €.tCO_2e^{-1}, when implementing agricultural practices selected on their a priori ability to increase SOC storage in France. In the UK (agricultural area 33% smaller than France), Eory et al (2015) estimated that 3,8 $MtCO_2e.yr^{-1}$ could be avoided for a cost lower than 225 £.tCO_2e^{-1}. In Ireland (agricultural area 5 times smaller than France), Teagasc (2012) estimated that less than 3,1 $MtCO_2e.yr^{-1}$ could be avoided at a cost lower than 150 €.tCO_2e^{-1} as opposed to 57 $MtCO_2e$ for the same marginal cost in our study. Although these estimates consider all mitigation practices while ours is restricted to carbon storage, they are comparatively much lower than our estimates for France. Indeed, out of our four major practices, they only consider cover crops but Teagasc (2012) limits its area base to spring barley and Eory et al (2015) does not quantify the SOC storage benefit of the practice. Eory et al (2015) also notes the high potential of agroforestry but does not quantify it in its MACC. For France, Pellerin et al. (2017) and Fellmann et al. (2021, as part of a more comprehensive EU-level assessment) also considered several mitigation practices and reported an abatement potential of about 32 $MtCO_2e\ yr^{-1}$ and 17,1 $MtCO_2e\ yr^{-1}$, respectively, at a cost lower than 250 € tCO_2e^{-1}. There again, our abatement potential estimate is comparatively much higher: Pellerin et al. (2017) did not consider grass/maize substitution and limited the cover crops potential to extension in space (while we are also considering extension in time). Regarding agroforestry and hedges, the estimates are similar except that Pellerin et al. (2017) arbitrarily limits the adoption to 7% of the area base. Fellmann et al. (2021) addressed different practices (except cover crops) and did not account for their carbon storage potential nor for CO_2 emissions.

It is difficult to compare our results with the other existing studies which tend to focus on a single practice. Despite this, two results seem to stand out from the literature (Table A8**Erreur ! Source du renvoi introuvable.**~~**Erreur ! Source du renvoi introuvable.**~~) regardless of the method used or the territory studied: i) conservation agriculture, based among others on reduced tillage and better crop rotations management, stands out for low carbon storage targets many in studies prior to Haddaway et al (2017); ii) drastic land use changes such as afforestation dominate for higher carbon storage targets (Newell et Stavins 2000, Plantinga et al. 1999, Stavins 1999, Lubowsky et al. 2006). For instance, in the USA, Lubowsky et al (2006) estimated that the afforestation of about 25 % of each state's agricultural land could increase carbon sequestration by 750 $MtC.yr^{-1}$ for a cost of 105 $€.tC^{-1}.yr^{-1}$. However, such large land use changes would compromise food security in the absence of dietary changes or waste reduction (Muller et al., 2017; Springmann et al., 2018) which is why they were not considered in our initial screening for carbon storage practices.

4.2. Negative implementation costs

As shown in Table 2~~Table 2~~, only “grass cover of vineyards” presents negative implementation costs in all regions, due to a decrease in crop management operations. This finding is consistent with the observation that a large share of French vineyards are already covered with grass (50% of the potential for permanent cover and 80 % of the potential for winter cover in 2013, Pellerin et al. 2020). However, these negative implementation costs probably also point out the existence of non-monetary barriers to adoption (e.g. labour availability constraints) and the possible importance of some unaccounted costs (e.g., transaction costs, potential impacts on wine yield and quality). In addition, they are sensitive to the hypotheses on the type of machinery used on vineyards.

4.3. Practices not considered

Because this study focused on farming practices able to increase carbon storage, a few mitigation levers typical of the agriculture and food sector such as shifting to plant-based diets or optimizing nitrogen fertilization (Arneth et al., 2019) were not considered. No-till farming and reduced tillage have been excluded due to their little potential for SOC storage in a temperate context (see introduction). The effect of conservation agriculture on SOC stocks is considered to arise essentially from the associated cover crops in temperate regions (Autret et al., 2016). Similarly, biochar was not retained because of its questioned potential in the temperate context (Arneth et al., 2019) and because to our knowledge it is currently not practiced at all in France. Moderate intensification of pastures turns out to be excluded in several regions as increased N_2O emissions from fertilizers more than offset the additional SOC storage. Most importantly with regards to the French and European carbon neutrality targets, the sylvo-pastoral potential for storage in tree biomass has been neglected. Using the same criteria as for agroforestry on arable soil, it would add a maximal area base of 2,25 Mha and a maximal biophysical potential of 7,4 $MtCO_2e.yr^{-1}$.

Last but not least of major carbon storage levers, wetland and peatland restoration was not included in this study. In the European context, peatland restoration has been estimated to avoid emissions between 2 and 34 $tCO_2e.ha^{-1}.yr^{-1}$ depending on climate, land-use and the extent of degradation (Pellerin et al., 2020; Barthelmes, 2018). Moreover, the EU potential for reducing emissions through peatland restoration has been estimated at around 109 $MtCO_2e\ yr^{-1}$ (Barthelmes, 2018). Due to the dearth of data on the abatement costs related to this practice in France, let alone their spatial heterogeneity, it was not possible to include it in this study. With only 140 kha of organic soils and 3,2 $MtCO_2e.yr^{-1}$ of reported emissions from wetland or peatland drainage (CITEPA, 2020), this shortfall does not undermine our main conclusions: for carbon prices higher than 28 €.tCO_2e^{-1}, the estimated abatement potential is more than 10 times higher than the 3,2 $MtCO_2e.yr^{-1}$ maximum potential for wetland and peatland restoration.

4.4. Main limitations of the study

In this study, we analysed which combinations of practices in each region would achieve GHG national mitigation targets at the lowest cost, considering the area base and relative abatement cost values of eight carbon storing practices at the regional level. Two types of limits were identified: a first set related to uncertainty of biophysical models and a second set related to the simplifying economic assumptions.

First, although the predictive value of STICS was shown to compare well with long term trials (Clivot et al., 2020), model outputs remain uncertain, in particular for the simulation of grassland management for which the simulated average is consistent with the literature but not the simulated range (Pellerin et al., 2020). For instance, the ability of STICS to simulate SOC dynamics in field crop rotations that include temporary grasslands is probably lower than for pure arable cropping systems because STICS has rarely been evaluated for such mixed cropping systems. The potential for additional SOC storage could therefore have been overestimated. In PaSim, permanent grasslands management in each pedoclimatic unit was not fully adapted to the local pedoclimatic condition. For instance, mowing and grazing dates were adapted with temperatures (degree days) but do not account for the bearing capacity of soils in case of grazing, thus potentially leading to an over-valuation of grazed grass. In addition, the models do not account for the reduced need for fertilization nor for the higher water retention capacity of soil, when the soil organic matter increases. By omitting potential savings of inputs such as N fertilizer, this study could have overestimated the cost of the storing practices or underestimated the associated GHG mitigation. The most important limit, which is also the most challenging to address, is that these models have only been scarcely validated on field trials for the specific practices considered (Levavasseur et al., 2021). For details on models and simulation plan limitations, see Graux et al., (2020), Launay et al., (2021) and Pellerin et al (2020).

For agroforestry and hedges, for which no model was available, the limit of our study lies in the lack of spatial heterogeneity in the regional carbon storage potential per hectare. While very diverse agroforestry systems and types of hedgerows exist in France (e.g. 22 types of hedgerows in France, https://afac-agroforesteries.fr/typologie-nationale-des-haies/), we defined only one scenario for each of these two practices, due to a limited number of observations about carbon sequestration in the literature (Cardinael et al 2017; 2018; Mayer et al 2022). For instance, we considered agroforestry systems with hybrid walnut and wild cherry trees for timber production. However, more diverse agroforestry systems with production of other goods such as fuelwood, fruits, nuts or even honey could potentially improve the economic performance of these systems and reduce the cost of carbon per hectare. This heterogeneity is nevertheless accounted for in the uncertainty range. Agroforestry could also be practiced on more marginal land with shallower soils (<1m depth) and with a higher decrease in crop yield, but the performance in terms of carbon sequestration and economic return could not be tested due to an absence of data.

Economic estimates also suffer from several simplifying assumptions. First, our cost estimations assume that overheads related to changes in cultivation operations per hectare are constant across farms. In reality, economies of scale are likely to occur, especially for mechanisation costs which depend on farm size, level of machine utilisation, machine characteristics and type of ownership. Further analysis would be needed to explore the impacts of these practices on different farm types. Second, costs were estimated for stable reference prices, without the simulation of market feedbacks. Likewise, crop areas and livestock production were maintained at levels close to those observed during the reference period, but crop yields varied from -26% to +18% depending on practices (Launay et al., 2021), and forage production was not kept constant. As crop supply is modified, it is very likely that market prices would also be modified but the economic model used in this study does not account for this effect. This in turn raises the issue of potential GHG emissions leakage outside of France (Frank et al., 2015), although we tried to limit this issue by excluding major land-use changes from the set of storing practices.

Eventually, the adoption of storing practices by farmers will depend on the type of public policies implemented. These policies have both direct effects (e.g., the impact of introducing a tax on net GHG budgets of farms) and indirect effects (induced by the adjustment of prices to market equilibrium). A tax is for instance likely to lead to a decrease in ruminant numbers, an increase in legumes and would induce profound changes in markets, farmers' incomes and food prices (Mosnier et al., 2019; Tang et al., 2018). Further studies considering the full range of market effects would be needed to test which public policies would be most effective in achieving the storage goals tested in this study.

Last but not least, one must bear in mind that the additional carbon storage allowed by a storing practice is i) «finite», i.e. it stops when a new carbon stock equilibrium is reached after a certain number of years; and ii) «non-permanent», i.e. the storing practice should continue, even once the equilibrium is reached, to prevent soil carbon release. For example, using “long-term average” formula mandated by carbon offset standards to deal with the cyclical nature of biomass changes in trees (e.g. Label Bas Carbone, 2020) would almost half the “physical” biomass storage potential we estimated over the first 30 years.

4.5. Possible improvements and perspectives

Our study is a first step towards the assessment of the synergy and trade-offs between carbon storage and GHG emissions reduction. It also raises the issue of the permanence of carbon storing practices, and how to ensure it, as achieving the annual additional storage potential estimated in our study involves their continuous implementation for 30 years. Moreover, additional storage must be considered in the context of climate change, with significant impacts not only on carbon dynamics (Crowther et al. 2016), but also on land use, production systems and practices.

Future work should include: i) simulations carried out under several climatic scenarios; ii) robustness or sensitivity analysis of the cost-effective strategy accounting for inter-annual price variations as well as the uncertainty surrounding additional carbon storage estimates. The next step would be to include our detailed results on practices (yields, technical costs variations, etc.) in microeconomic supply models, to assess more accurately the opportunity cost of practices and various abatement strategies and to help designing cost-effective climate policies. Research on how to overcome the barriers to the adoption of the cost-effective practices by farmers is also needed.

5. Conclusion

Eight potential carbon storing practices relevant to the French metropolitan territory were identified based on a literature review: cover crops; new carbon inputs (e.g. sludge); replacement of silage maize with temporary grasslands; moderate intensification of extensive grasslands (+50kgN.ha^{-1}); animal grazing instead of mowing; agroforestry; hedges; and grass cover of vineyards. The carbon storage potential of the first 5 practices was simulated at a very fine spatial scale, together with their total GHG budget, considering the spatial heterogeneity in pedoclimatic conditions and cropping techniques. No model being available for the last 3 practices, their carbon storage and net mitigation potential was assessed based on a comprehensive literature review and expert knowledge. After assessing the implementation cost at the regional scale, the potential applicability, and the net mitigation potential of each carbon storing practice, we integrated them into an economic model (BANCO).

We find a potential for net GHG abatement of 58,9 $MtCO2e.yr^{-1}$ for a total cost for farmers of circa 2.5 $G€.yr^{-1}$, which would offset 13% of national GHG emissions and 77% of the agricultural sector emissions. 99,7% of this abatement potential can be achieved at a lower cost than 250 $€.tCO_2e^{-1}$ (i.e. the 2030 target carbon price in France). The abatement potential mostly arises from additional carbon storage in soil (28,2 $MtCO2e.yr^{-1}$, i.e. 48%) and biomass (43%), and 98% of the total additional SOC storage potential is found in arable soils, where initial SOC stocks are low. Reaching high mitigation targets mostly relies on the full deployment of four key practices which add up to 97% of the net abatement potential: agroforestry, cover crops, hedges, and the expansion of temporary grasslands – at the expense of silage maize – in crop rotations. This finding supports the strategy of the European Commission which includes these four practices in its list of six major storing practices, in addition to afforestation and peatland restoration (European Commission, 2021).

The associated additional carbon sink in soil and biomass amounts to 53,6 $MtCO_2e$ per year and is 435% higher than the 10 $MtCO_2e$ yr^{-1} storage objective assigned to agricultural land in the climate neutrality strategy (MTES, 2020). Adding the sylvo-pastoral potential would further raise this additional carbon sink to 60 $MtCO_2e$ per year. This figure offers a whiff of optimism into the otherwise bleak assessment of the chances that France meets its 2050 climate neutrality target (e.g. Haut Conseil pour le Climat, 2021). This good news should be tempered by the fact that our estimate of “additional carbon storage” likely comes on top of currently unaccounted emissions from cropland soils: the French national inventory currently reports a net sequestration of 1 $MtCO_2e.yr^{-1}$ whereas French cropland soils are most likely net emitters, with an order of magnitude estimated at 0.19 $tC.ha^{-1}.yr^{-1}$ (Pellerin et al, 2020).

The fine resolution of both agronomic and economic estimates also shows the importance of taking into account the biophysical and agricultural specificities of each region for the design of a cost-effective policy, for there is not "one good carbon storing practice" to increase carbon storage in soils, rather a combination of good practices at the right place. Our results therefore provide useful information for policy makers, on the potential and cost of carbon storage at a fine spatial scale. They can be used in the frame of the CAP reform for the design of the national voluntary eco-scheme, for instance. A policy aiming at supporting additional SOC storage in arable land must not come at the expense of the preservation of high existing carbon stocks in permanent grasslands and forests.

Finally, agriculture is at the center of several challenges (e.g. water quality, biodiversity conservation, food security, bioeconomy, and indeed climate change). Given the high cost of some practices such as agroforestry and hedges, and the fact that the practices studied provide services other than just storing carbon in soil, there is a need to ensure coherence between the existing policies and, ideally, bundles of ecosystemic services should be accounted for in an integrated policy.

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Appendices

A.1 Methodology, data, and data sources

Type of calculation	**Data requirements**	**Data sources**
Carbon storage and GHG budget	Soil data (characteristics and use)	Geographic database for land use in France on a scale of 1/1 000 000 (BDGSF, INRA Infosol) Mulder et al. (2016) for initial SOC stocks, 90*90m grid
	Climate data	SAFRAN data base, 8x8 km grid (Meteo France, processed by INRA Agroclim)
	Crop sequences	Derived from the French Land Parcel Identification System (INRA ODR)
	Cropping practices Permanent grasslands management	Crop practices survey, 2006 and 2011 (SSP) Nitrate Directive 2012 for intercropping management Permanent grasslands survey (SSP) ISOP system (Information and objective monitoring of grasslands)
	GHG emission factors and equations, Emissions induced upstream/downstream	IPCC 2006, French Inventory (CITEPA), Carbone® database (ADEME)
Implementation costs	Crop reference prices and yields Crop gross margins	FADN (2009-2013 ; SSP), Annual agricultural statistics (2009-2013 ; SSP), coefficient from General Association of Corn Producers for fodder maize
	Input prices	Eurostat, national statistics
	Crop management operations costs	CUMA (machinery cooperative) third-party service delivery scale (FNCUMA, APCA)
Potential applicability	Crop areas and livestock numbers	Annual agricultural statistics (2009-2013 ; SSP)
	Limiting soil characteristics	BDGSF (INRA Infosol)

Table A 1 Data sources per calculation type

SOC storing practices	**Implementation criteria**
Expansion of cover crops	- Extension of the covers in place - Insertion of new cover crops in all fallows lasting more than two months

Expansion of temporary grasslands	- Extension (1-2 extra years) of existing temporary grasslands in crop rotations and substitution of fodder maize by temporary grasslands in crop rotations. - Replacement of silage maize by three years of temporary grasslands in crop rotations
New organic C inputs	- Random application of new products in rotations that were not receiving organic fertilization
Moderate intensification of extensive grasslands	- Supply of 50 kgN/ha/year for unfertilized or low-fertilized (< 50kgN/ha/year) permanent grassland
Grazing instead of mowing permanent grasslands	- For intensively mown permanent grasslands (4 cuts), 2 cuts are substituted by grazing events - For highly used permanent grasslands (2 cuts + 2 grazing events), 1 cut is substituted by 1 grazing event
Grass cover of vineyards (permanent)	- Vineyards with bare soils, winter grass cover, or grass cover every other inter-row - Excluding Mediterranean and Cognac vineyards (potential yield loss too important) - Soil stoniness > 35% and/or soil with stones> 7,5cm diameter
Grass cover of vineyards (winter)	- Bare inter-rows
Agroforestry	- Croplands ≥ 1 hectare - Soil depth ≥ 1m - No hydromorphic soils
Hedges	- Group of fields ≥ 8 hectares - Soil depth ≥ 50 cm

Table A 2 Implementation criteria of the SOC storing practices

SOC storing practices	**Soil carbon stock conversion factor from 0-30cm to 0-100cm soil horizon**
Expansion of cover crops	1,70603359
Expansion of temporary grasslands	1,68125666
New organic C inputs	1,71418257
Moderate intensification of extensive permanent grasslands	1,21033939
Grazing instead of mowing permanent grasslands	1,36695288
Grass cover of vineyards (permanent and winter)	1,886
Agroforestry	1,886
Hedges	1,886

Table A 3. Factor to convert carbon stock of the 0-30cm soil horizon into carbon stock of the whole soil profile (0-100cm horizon)

A.2 Area base, storage potential, net GHG budget and cost per storing practice and region

Table A 4 Area base of each practice in each region, in hectare. Adapted from [dataset] Bamière et al. (2021).

Region code	Region name	Cover crops	New organic resources	Expansion of temporary grasslands	Agroforestry	Hedges	Moderate intensification of permanent grasslands	Grazing instead of mowing	Grass cover of vineyards : permanent	Grass cover of vineyards : winter
11	Ile-de-France	508 260	149 706	993	219 634	417 204	20 028	0	0	0
21	Champagne-Ardenne	1 162 875	58 142	83 092	438 119	851 270	190 031	0	2 742	23 758
22	Picardie	1 062 450	29 014	106 841	628 755	745 768	10 486	0	0	0
23	Haute-Normandie	375 442	37 845	109 100	387 684	346 455	33 888	0	0	0
24	Centre	1 854 283	131 111	259 262	583 058	1 078 759	180 776	0	10 265	10 427
25	Basse-Normandie	658 484	37 405	453 383	208 961	272 307	219 105	11 419	0	0
26	Bourgogne	947 045	52 447	153 418	207 839	435 212	642 999	0	9 065	19 971
31	Nord-Pas-De-Calais	543 215	18 543	171 550	345 223	303 814	26 323	0	0	0
41	Lorraine	681 569	68 410	184 786	210 220	428 605	205 823	0	0	0
42	Alsace	207 262	31 320	21 089	60 254	168 356	44 665	0	9 667	800
43	Franche-Comte	268 794	44 407	92 110	52 882	124 325	213 932	0	0	0
52	Pays de la Loire	1 389 317	48 522	1 211 196	472 101	655 169	280 570	0	16 757	15 529
53	Bretagne	1 274 339	34 142	1 311 486	411 626	700 419	68 802	351	0	0
54	Poitou-Charentes	1 296 033	81 914	476 073	345 809	558 279	130 814	0	11 127	30 692
72	Aquitaine	750 086	141 558	319 528	208 245	480 029	172 507	0	61 242	18 798
73	Midi-Pyrenees	1 402 295	138 804	675 886	272 197	522 445	328 574	635	18 796	4 353
74	Limousin	280 049	78 884	277 854	20 581	126 645	337 215	4 335	0	0
82	Rhone-Alpes	518 855	127 926	316 425	109 564	198 489	399 390	2 879	11 827	27 152
83	Auvergne	544 957	22 610	295 257	97 266	228 192	340 210	53 861	0	0
91	Languedoc-Roussillon	186 462	48 395	59 343	23 207	113 108	38 788	14 420	0	191 483
93	Provence-Alpes-Cote-Azur	114 555	83 851	56 236	22 361	71 056	56 273	0	0	69 569
94	Corse	na	na	na	494	3 484	na	na	na	na

Table A 5 Implementation cost, per hectare of area base, of each practice in each region (€ ha[-1]). Note: a negative cost represents a gain for the farmer, a positive cost a shortfall, compared to the baseline scenario. Adapted from [dataset] Bamière et al. (2021).

Region code	Region name	Cover crops	New organic resources	Expansion of temporary grasslands	Agroforestry	Hedges	Moderate intensification of permanent grasslands	Grazing instead of mowing	Grass cover of vineyards : permanent	Grass cover of vineyards : winter
11	Ile-de-France	28,6	-92,0	19,8	139,0	71,9	26,3			
21	Champagne-Ardenne	27,5	41,4	131,3	125,1	71,6	24,0		-25,5	-15,2
22	Picardie	30,9	29,2	233,5	156,9	76,2	29,2			
23	Haute-Normandie	18,9	50,8	197,0	144,6	75,5	24,0			
24	Centre	27,6	8,6	49,3	114,4	69,9	26,0		-25,7	-15,2
25	Basse-Normandie	38,6	28,1	263,4	107,6	73,0	24,2	-38,1		
26	Bourgogne	36,1	16,3	-40,6	92,7	69,9	32,5		-25,3	-15,2
31	Nord-Pas-De-Calais	21,7	229,0	313,7	178,8	86,5	37,7			
41	Lorraine	68,2	21,5	102,4	105,6	71,3	14,4			
42	Alsace	146,9	52,2	31,2	133,1	84,7	17,5		-27,4	-15,2
43	Franche-Comte	27,3	-21,6	4,8	90,4	72,0	12,1			
52	Pays de la Loire	24,4	214,5	67,9	95,2	71,3	29,2		-25,8	-15,2
53	Bretagne	38,4	268,9	142,8	91,7	75,1	31,0	-84,7		
54	Poitou-Charentes	29,5	28,0	13,9	96,0	73,9	31,9		-26,9	-15,2
72	Aquitaine	109,4	32,2	112,2	101,4	75,3	31,3		-27,4	-15,2
73	Midi-Pyrenees	43,7	-6,5	19,2	85,7	71,1	25,9	-7,2	-22,2	-15,2
74	Limousin	40,0	30,8	28,7	72,7	71,6	38,2	145,8		
82	Rhone-Alpes	26,2	25,2	24,5	91,7	74,3	20,3	94,6	-25,4	-15,2
83	Auvergne	51,5	48,1	11,4	84,5	71,8	34,8	112,6		
91	Languedoc-Roussillon	38,4	22,8	-5,3	68,7	64,6	35,9	-3,4		-15,2
93	Provence-Alpes-Cote-Azur	11,9	-12,6	16,5	63,3	58,4	37,5			-15,2
94	Corse	na	na	na	67,4	54,1	na	na		na

Table A 6 Net GHG budget per hectare of area base for each practice in each region ($tCO_2e\ ha^{-1}$). Note : a negative value means a net removal of carbon from the atmosphere compared to the baseline scenario. Adapted from [dataset] Bamière et al. (2021).

Region code	Region name	Cover crops	New organic resources	Expansion of temporary grasslands	Agroforestry	Hedges	Moderate intensification of permanent grasslands	Grazing instead of mowing	Grass cover of vineyards : permanent	Grass cover of vineyards : winter
11	Ile-de-France	-1,079	-0,668	-0,087	-5,606	-1,190	0,156			
21	Champagne-Ardenne	-0,869	-0,396	-2,448	-5,607	-1,223	0,101		-1,885	-1,087
22	Picardie	-0,749	-0,494	-2,654	-5,629	-1,225	0,192			
23	Haute-Normandie	-0,528	-0,488	-2,616	-5,585	-1,231	0,033			
24	Centre	-1,340	-0,265	-0,470	-5,436	-1,199	0,030		-1,755	-1,087
25	Basse-Normandie	-0,606	-0,554	-2,960	-5,332	-1,244	0,022	-0,811		
26	Bourgogne	-1,299	-0,368	-0,848	-5,420	-1,240	-0,326		-1,892	-1,087
31	Nord-Pas-De-Calais	-0,335	-0,495	-3,014	-5,593	-1,313	0,119			
41	Lorraine	-1,008	-0,422	-2,372	-5,536	-1,241	0,135			
42	Alsace	-0,482	-0,111	-0,410	-5,511	-1,385	0,264		-1,256	-1,087
43	Franche-Comte	-1,055	-0,414	-1,239	-5,230	-1,266	-0,246			
52	Pays de la Loire	-0,141	-0,259	-0,791	-4,789	-1,198	0,246		-1,725	-1,087
53	Bretagne	-0,163	-0,225	-0,850	-4,750	-1,269	0,579	-0,173		
54	Poitou-Charentes	-0,841	-0,171	-0,423	-5,129	-1,264	0,398		-1,514	-1,087
72	Aquitaine	-0,797	-0,228	-0,451	-5,173	-1,286	0,199		-1,359	-1,087
73	Midi-Pyrenees	-0,593	-0,215	-0,523	-4,953	-1,228	0,100	-1,149	-1,586	-1,087
74	Limousin	-0,368	-0,196	-0,106	-4,493	-1,217	0,169	-0,497		
82	Rhone-Alpes	-0,424	-0,212	-0,453	-4,912	-1,277	0,122	-0,681	-1,826	-1,087
83	Auvergne	-1,307	-0,289	-0,738	-4,887	-1,228	-0,256	-0,901		
91	Languedoc-Roussillon	-0,635	-0,215	-0,531	-5,092	-1,187	0,497	-0,724		-1,087
93	Provence-Alpes-Cote-Azur	-0,584	-0,330	-0,449	-5,000	-1,107	1,131	0		-1,087
94	Corse				-4,507	-0,974				

Table A 7 Detail of the net GHG budget per practice and region : additional SOC storage (SOC, $tCO_2e\ ha^{-1}$), additional carbon storage in biomass (B, $tCO_2e\ ha^{-1}$), variation of GHG emissions (GHG, $tCO_2e\ ha^{-1}$), per hectare of area base. Note : a negative value means an increase in carbon storage or a decrease in GHG emission compared to the baseline scenario. (ECC : expansion of cover crops ; NOR : new organic resources ; ETP : expansion of temporary grasslands ; AF : agroforestry ; H : hedge ; MIPG : moderate intensification of permanent grasslands ; GIM : grazing instead of mowing ; GCVP/W: grass cover of vineyards permanent/winter) Adapted from [dataset] Bamière et al. (2021).

	ECC		NOR		ETG		AF			H			MIPG		GIM		GCVP		GCVW	
Region code	SOC	GHG	SOC	GHG	SOC	GHG	SOC	B	GHG	SOC	B	GHG	SOC	GHG	SOC	GHG	SOC	GHG	SOC	GHG
11	-1,099	0,020	-0,722	0,054	0,010	-0,097	-1,718	-3,300	-0,588	-0,128	-0,833	-0,228	-0,644	0,800						
21	-0,883	0,014	-0,444	0,048	-1,964	-0,484	-1,702	-3,300	-0,606	-0,130	-0,858	-0,234	-0,583	0,685			-2,201	0,317	-1,100	0,013
22	-0,746	-0,003	-0,570	0,077	-2,356	-0,298	-1,713	-3,300	-0,616	-0,131	-0,857	-0,237	-0,477	0,668						
23	-0,539	0,011	-0,543	0,056	-2,314	-0,302	-1,670	-3,300	-0,615	-0,129	-0,865	-0,237	-0,648	0,680						
24	-1,392	0,052	-0,294	0,028	-0,307	-0,163	-1,558	-3,300	-0,578	-0,120	-0,851	-0,227	-0,731	0,761			-2,015	0,261	-1,100	0,013
25	-0,625	0,020	-0,594	0,040	-2,564	-0,397	-1,460	-3,300	-0,572	-0,120	-0,896	-0,229	-0,705	0,727	-1,237	0,427				
26	-1,372	0,073	-0,396	0,028	-0,615	-0,233	-1,555	-3,300	-0,565	-0,125	-0,888	-0,227	-1,108	0,783			-2,212	0,320	-1,100	0,013
31	-0,337	0,002	-0,600	0,104	-2,747	-0,268	-1,699	-3,300	-0,594	-0,142	-0,934	-0,237	-0,516	0,635						
41	-1,033	0,025	-0,461	0,039	-1,929	-0,442	-1,635	-3,300	-0,601	-0,129	-0,877	-0,235	-0,498	0,633						
42	-0,488	0,006	-0,066	-0,045	-0,269	-0,142	-1,597	-3,300	-0,613	-0,144	-0,995	-0,247	-0,451	0,715			-1,301	0,046	-1,100	0,013
43	-1,144	0,089	-0,469	0,055	-1,009	-0,230	-1,367	-3,300	-0,563	-0,117	-0,921	-0,228	-0,741	0,495						
52	-0,148	0,007	-0,312	0,053	-0,618	-0,173	-0,971	-3,300	-0,519	-0,087	-0,895	-0,216	-0,619	0,865			-1,972	0,248	-1,100	0,013
53	-0,163	0,000	-0,288	0,063	-0,632	-0,218	-0,914	-3,300	-0,536	-0,089	-0,957	-0,224	-0,479	1,058	-0,111	-0,061				
54	-0,878	0,037	-0,202	0,032	-0,229	-0,194	-1,279	-3,300	-0,549	-0,112	-0,927	-0,225	-0,615	1,013			-1,671	0,157	-1,100	0,013
72	-0,837	0,040	-0,272	0,044	-0,247	-0,205	-1,292	-3,300	-0,582	-0,114	-0,938	-0,234	-0,699	0,898			-1,449	0,090	-1,100	0,013
73	-0,587	-0,005	-0,232	0,017	-0,358	-0,165	-1,139	-3,300	-0,514	-0,100	-0,912	-0,216	-0,644	0,744	-1,962	0,813	-1,774	0,188	-1,100	0,013
74	-0,372	0,003	-0,209	0,013	0,007	-0,113	-0,707	-3,300	-0,485	-0,073	-0,935	-0,209	-0,765	0,934	-1,032	0,535				
82	-0,466	0,041	-0,210	-0,002	-0,266	-0,187	-1,048	-3,300	-0,563	-0,098	-0,949	-0,230	-0,550	0,672	-1,151	0,469	-2,117	0,292	-1,100	0,013
83	-1,311	0,004	-0,356	0,067	-0,523	-0,215	-1,071	-3,300	-0,516	-0,096	-0,915	-0,216	-1,118	0,863	-1,319	0,418				
91	-0,673	0,038	-0,267	0,051	-0,328	-0,203	-1,292	-3,300	-0,500	-0,106	-0,871	-0,210	-0,428	0,925	-1,684	0,961			-1,100	0,013
93	-0,629	0,045	-0,367	0,037	-0,261	-0,188	-1,153	-3,300	-0,547	-0,089	-0,801	-0,217	-0,116	1,247					-1,100	0,013
94							-0,706	-3,300	-0,501	-0,056	-0,716	-0,203								

A3 Literature review of SOC storage opportunity costs

Study	Scope of the GHG assessment[2]	Approach[3]	SOC storing practices	Study area	Cost (€ tC^{-1} [4])	Amount of carbon stored in MtC yr^{-1} [5]
Antle et al., 2001	Soil	EM	Conversion of arable land to grassland	Montana zone 1	80 – 415	0,15 – 1,35
			Continuous cropping system (no fallow)	Montana zone 1	20 – 105	1,86 – 4,32
			Conversion of arable land to grassland	Montana zone 2	85 – 440	0,46 – 0,75
			Continuous cropping system (no fallow)	Montana zone 2	25 – 115	0,88 – 2,15
Antle et al., 2007	Soil	EM	Conservation agriculture (wheat system)	Centre US	0 – 170	0 – 0,5
			Conservation agriculture (corn-soybean system)	Center US	0 – 170	0 – 0,7
			Reduction of fallow land	Center US	0 – 170	0 – 0,9

[2] Soil carbon sequestration only or complete GHG balance.

[3] Methodology based on a mathematical programming model (MP), an econometric model (EM), a partial/general equilibrium model (PEM, GEM), an "engineering" type model (ING). These approaches can be coupled or not with other types of models (e.g. biophysical).

[4] In euros per ton of carbon. The ranges correspond to the costs associated with the different levels of carbon sequestration presented in the next column. These costs are calculated relative to a reference situation in which agricultural practices remain unchanged. Dollar-Euro exchange rate of sept. 2018.

[5] In million tons of carbon per year (unless otherwise noted in parentheses). This is the additional amount of carbon sequestered in the studied area compared to the baseline scenario.

De Cara et al., 2006	GHG	MP	No-till or reduced tillage	EU 17	25 – 125	2 - 7
Feng et al., 2006	Soil	EM	Conservation agriculture	Iowa	0 – 170	0 – 5
			Land retirement	Iowa	0 – 170	0 – 20
Frank et al., 2015	Soil	PEM	No-till or reduced tillage	Europe 27	10 – 100	2 - 10
Kragt et al., 2012	Soil	MP	Introduction of grasslands in crop rotations	Western Australia	5 – 132	0,01 – 0,04
Lubowski et al., 2006	Soil	EM	Afforestation	US	0 – 105	0 – 750
McCarl et al., 2001	Soil	PEM	Conservation agriculture	US	12	60
			Afforestation	US	46	200
Paustch et al., 2001	Soil	EM	Conservation agriculture	Iowa	0 – 515	0 – 2
Pellerin et al., 2013	GHG	ING	No tillage	France	2	1
			Introduction of cover crops	France	43	0,3
			Agroforestry and hedgerows	France	4	0,4
			Extension of the duration of temporary grasslands	France	60	0,4
Plantinga et al., 1999	Soil	EM	Afforestation	Maine	0 – 95	0 – 5
			Afforestation	South Carolina	0 – 40	0 – 16
			Afforestation	Wisconsin	0 – 65	0 – 60

Table A8 Literature review of existing economic studies on soil carbon storage