Article

Cost-effective mitigation of greenhouse gas emissions in agriculture

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Abstract: Climate change from anthropogenic activities represents a serious threat to life in earth. Agriculture releases significant emissions of greenhouse gases (GHG), but also offers low-cost opportunities to mitigate GHG emissions. This paper assesses agricultural GHG emissions in Aragon, one important and representative region for agriculture in Spain. The Marginal Abatement Cost Curve (MACC) approach is used to analyze the abatement potential and cost-efficiency of mitigation measures under several scenarios, with and without taking into account the interaction among measures and their transaction costs. The assessment identifies the environmental and economic outcomes of different combinations of measures. Moreover, we develop future mitigation scenarios for agriculture toward the year 2050, in order to assess the impacts on GHG emissions. Results highlight the importance of assessing biophysical processes in mitigation measures, and the significant effects of interactions between measures that reduce the abatement potential and worsen the cost-efficiency. The inclusion of transaction costs provides a better ranking of measures and a more accurate estimation of implementation costs. The scenario analysis shows how the combinations of measures could reduce emissions and promote sustainable agriculture in the future.

Keywords: Climate change; mitigation measures; biophysical processes; cost-efficiency; abatement costs; transaction costs; policy scenarios.

1. Introduction

Climate change is the consequence of massive greenhouse gas (GHG) emissions from human activities. These emissions are driven by many factors such as the growth of population and economic activities, the use of fossil fuels, the changes in land use (urbanization, deforestation, desertification...), and the intensification of agriculture [1] . The high concentrations of GHG in the atmosphere absorb the infrared radiation and are responsible for the increase of one degree in the global annual temperatures between 1960 and 2017 [2, 3]. GHG emissions are modifying the global climate system, with future predictions of higher temperatures, lower rainfall in arid and semi-arid regions, rise in the sea level, and higher frequency and intensity of extreme weather events [4, 5]. Climate variability is affecting the availability and quality of water and water dependent ecosystems. Freshwater and marine species are modifying their geographic distribution areas and their seasonal activities, increasing the risk of extinction. Liu et al. [6] show also the importance of understanding changing water temperatures in rivers for addressing good riverine environmental management. The increase of anthropogenic GHG emissions affects the distribution of precipitations and modifies the fluvial processes [7]. These climate change impacts are considered a serious threat to the sustainable development of human societies, and require immediate action [8]. Many scientist indicate that the anthropogenic GHG pollution is one of the greatest threat of our time [9, 10].

The United Nations Framework Convention on Climate Change (UNFCCC) was created in 1992 to respond to the threat of climate change, and the UNFCCC developed the Kyoto Protocol in 1997. However, the effect of this protocol on the reduction of global emissions has been only marginal. The latest policy initiative has been the Paris Agreement of 2015, which aims to ensure that global warming does not exceed 1.5 °C and so limiting the risks and impacts of climate change. This Agreement makes it clear that the global community must address the effects of climate change on agriculture in order to guarantee global food security [11]. In Europe, the concern for the environment has increased in recent years leading to ambitious abatement goals with GHG reductions of 20% in 2020, 40% being increased to 55% in 2030, and 80% in 2050.

The agricultural sector is important for food security in all countries, but generates also negative impacts on the environment and is responsible for 13.5% of global GHG emissions [3]. In Spain, the agricultural sector emits 10% of the total emissions of the country and it is an important source of non-CO_2 emissions [12]. Agricultural and forestry activities are a source of low-cost opportunities to mitigate these emissions compared to other economic sectors. Soil carbon sequestration is a strategy that can be applied at widespread scale with a large potential to slow down global warming, mitigate GHG emissions, and reduce the concentration of CO_2 in the atmosphere [13, 14]. In addition, the enhancement of natural carbon sinks is considered as an important management tool to reduce atmospheric CO_2 emissions [14]. Good forest management and better soil management can substantially reduce GHG emissions, by increasing the carbon sequestration in soils and the amount of organic matter, and by adjusting the soil nitrogen cycle. The control of nitrogen entry into the soil is also a good practice to reduce direct and indirect N_2O emissions and nitrate content in water bodies. Measures related to nitrogen fertilization management improve the efficiency of nitrogen use. These practices improve soil fertility, optimize crop productivity [15], and provide greater biodiversity and less erosion, runoff and pollution loads to the atmosphere and water media. Therefore, those practices are relevant to decision makers for the design of sustainable policies.

Sustainable agriculture, food security and well-being of farmers require an integrated analysis of the performance of the agricultural sector. Several studies investigate the problem of GHG emissions in agriculture at local, regional and global levels, assessing a wide range of mitigation measures [16, 17, 18, 19, 20, 21]. This paper analyzes the underlying biophysical processes in order to evaluate different policy measures for mitigating GHG emissions and for reducing the social and environmental impacts of climate change. To reach this objective, we analyze a nonpoint pollution problem located in northeasters of Spain (Aragon) looking at the abatement potential and the cost-efficiency of different mitigation measures. The abatement measures are evaluated individually and in combination using the Marginal Abatement Cost Curve (MACC) approach. We develop also several mitigation policy scenarios up to 2050 for agriculture to assess the impacts of these policies on the balance of GHG emissions. Climate change and agricultural nonpoint pollution are global problems that affect all regions in the world, however it is important to analyze the problem locally in order to gain knowledge on the best alternatives for atmospheric and water pollution abatement in each zone. The purpose is to promote awareness and mobilize society to confront climate change.

The assessment of the environmental, political, economic and social impacts in each region is a precondition to confront climate change, global warming, and pollution problems with efficient measures adapted to local specific conditions. The MACC approach has been used to analyze the efficiency of mitigation measures in different situations with and without taking into account the transaction costs and the interaction between measures, by estimating the environmental and economic outcomes.

Aragon is an interesting case to evaluate nonpoint pollution, because of the importance of the agricultural sector, with large swineherds and extensive irrigation. Surface and ground water bodies in Aragon are affected by agricultural pollution and 4% of the drinking water supply areas are not complying water quality standards because of excessive nitrate levels, with an affected population of 12,000 inhabitants [22, 23]. In addition, the potential impact of climate change differs across Europe but it is especially strong in the south of Europe where countries are more vulnerable to climate change [24]. The tasks for the study include the evaluation of the biophysical processes in order to estimate nitrate leaching from crops and nitrogen excreted from livestock.

The contribution of this study to previous literature is to provide a detailed assessment of GHG mitigation measures in agriculture and forestry. The outcomes from these measures include the enhancement of soil carbon sequestration, efficiency gains in the use of nitrogen and water, improvements in livestock digestion, and reduced nitrogen pollution loads from crops and livestock. Furthermore, the consideration of transaction costs is included in the analysis providing a better ranking of measures and a more accurate estimation of implementation costs. In addition, the estimation of the MACC for individual measures has been extended to the combination of measures, where measures interact with each other.

This information can contribute to the ongoing policy discussion and the improvement of decision-making on mitigation. The results of this paper highlight the importance of including the transaction cost for a more reliable appraisal of the costs of implementation. Our results indicate also that the interaction between measures reduce the abatement rate of subsequent measures and worsens their cost-efficiency, especially for measures with positive costs. The large differences between the efficiency of individual or combined measures show the importance of considering the interaction of measures for policy design.

The paper is organized as follows. Section 2 presents a general description of the study area and the main agricultural activities in the region. Section 3 describes the main biophysical processes in agricultural nonpoint pollution and the abatement alternatives. Then the MACC of measures is developed and the abatement scenarios up to 2050 are described. Section 4 presents the main results of MACC for individual and combined measures, and the impacts on the GHG balance of emissions in 2050. Section 5 summarizes the main conclusions.

2. Study area

In this study, Aragon is an illustrative case, and the results from mitigation measures and policy scenarios could provide a relevant insight to other regions in countries confronting high levels of agricultural nonpoint pollution into the atmosphere and water media. The State of Aragon is located in northeastern Spain in the Middle Ebro Valley, covering an area close to 48,000 km^2 [25]. Most land is for agricultural and forestry use, with 49% being agricultural areas and 50% woodland and forested areas covered with vegetation, open and closed forest. The use of land in agriculture is characterized by an extensive rainfed area (66%), coupled with a substantial irrigated area (34%). The major cultivated crop acreage are barley (55%) and wheat (27%) in dryland, and barley (27%), corn (22%) and alfalfa (20%) in irrigated land. The main irrigation systems are surface irrigation (47%) followed by sprinkle in arable crops (38%) and drip in woody crops (15%) (MAPAMA 2017b). Vineyards, olive and almond trees are the most important fruit-trees in the region in terms of area and profitability. Livestock production represents 63% of the net income in the agricultural sector in Aragon and crop production 34%. The swine sector has large economic and social importance representing 62% of livestock production and 36% of agricultural production (Government of Aragon 2017).

The forested area is located in Huesca (37%), Teruel (37%) and Zaragoza (26%). Carbon sequestration by forests is an important factor to combat climate change since forests capture close to 3 $MtCO_2e$, which could be valued at 116 M€ using the estimate of 40 €/tCO_2e for the social cost of carbon from the OECD [26]. The species that fix the largest amount of carbon are pine forests (38%), followed by oak (19%).

The types of crops and animal species analyzed in this study have been selected by their level of activity and profitability. The selected crops are wheat, barley , almonds, olives, and vineyard cultivated in dryland and irrigated land, and alfalfa, maize, onion, rice, pea, apple, peach, cherry cultivated only in irrigated lands. These crops represent 65% of the total crop area in the region. The selected livestock species are cattle, sheep, pigs and chicken (Figure 1).

3. Materials and Methods

The methodology to estimate agricultural GHG emissions is the Level 1 procedure of the IPCC method (Tier 1). The main source of non-CO_2 emissions considered in this study are direct and indirect nitrous oxides emissions (N_2O) from fertilizers, methane (CH_4) from enteric fermentation, and N_2O and CH_4 from manure management. The procedure consists in multiplying the emission factors (EF) by the specific data of the region, which are surface of crop i (X_i), heads of livestock j (C_j), fertilization (N_i), nitrogen leaching (L_i), and nitrogen excreted by each animal j (Nex_j) [27, 28]. The emissions are given by the following equations:

Direct emissions of N_2O = $\sum_{i=1}^{n}(N_i \,.\, X_i . EF_i . (44/28). WP_{N_2O})/1,000$ (1)

Indirect emissions of N_2O = $\sum_{i=1}^{n}(L_i \,.\, X_i . EF_2 \,.\, (44/28). WP_{N_2O})/1,000$ (2)

CH_4 from enteric fermentation = $\sum_{j=1}^{n}(C_J \,.\, EF_{3j} \,.\, WP_{CH_4})/1,000$ (3)

N_2O emissions from manure management= $\sum_{j,k}^{n}(C_j \,.\, Nex_j . EF_{4k} \,.\, (44/28). WP_{N_2O})/1,000$ (4)

CH_4 emissions from manure management = $\sum_{j=1}^{n}(C_J \,.\, EF_{5j} \,.\, WP_{CH_4})/1,000$ (5)

The coefficient (44/28) is the molecular weight ratio between N_2O and nitrogen (N_2), and WP is the warming potential of the greenhouse effect for CH_4 and N_2O.

The approach used to estimate the abatement potential from individual measures and from combined measures (taking into account interaction between measures) is the marginal abatement cost curve (MACC). This tool is very appropriate for a reliable assessment of mitigation policies. The calculation of the balance of GHG emissions and the cost-efficiency of measures is performed evaluating the economic and environmental outcomes from agriculture in each municipal district.

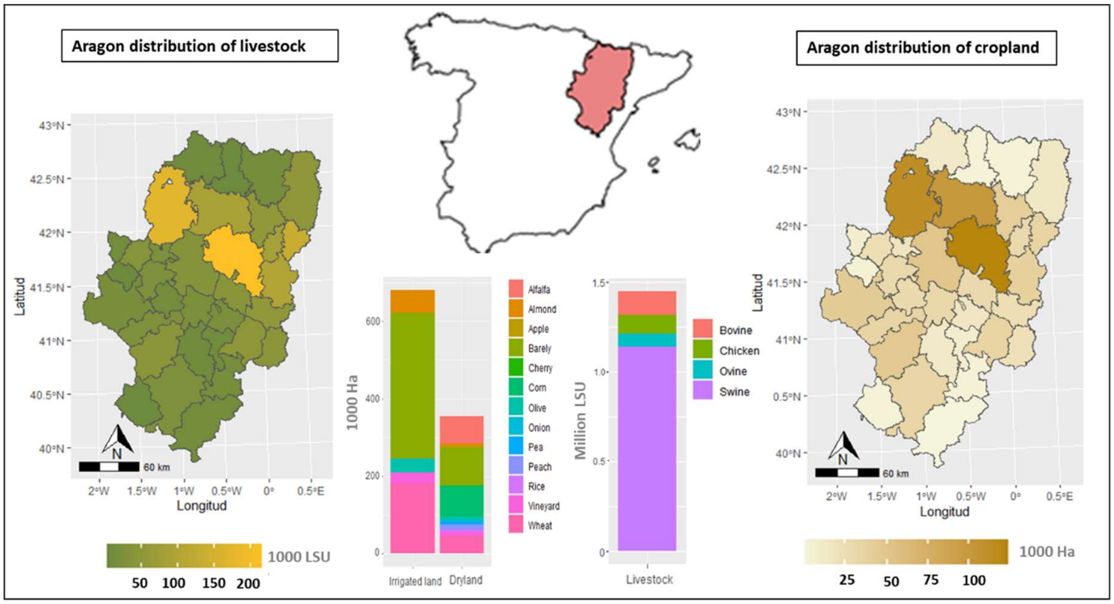

Figure 1. Main field crops, fruit trees and livestock herds. (LSU is Livestock Unit equivalent)

The methodology used to estimate the potential for mitigation is the following: first, we select the most applicable and efficient mitigation measures in Aragon and collect the information on the costs and efficiency of each measure m. The selection of measures is based on technical information and biophysical processes such as carbon sequestration in soils, the efficiency in nitrogen and water use, and the reduction of nitrogen excreted from livestock. The description and selection of mitigation measures are presented below. In addition, we analyze the adoption and degree of applicability of selected measures in the region depending on land use data and experts' judgment.

Second, the abatement potential of each measure m is determined from the abatement rate AR_{mi} or AR_{mj} of each crop *i* or each species of animal *j*, and then the abatement rates are multiplied by the acreage X_i or animal heads H_j covered by the measure (Equation (6)). PC_m is the private cost of each measure m that represent the difference between the benefits B_m (increase in yields or decrease in production costs) and the costs of implementing measure C_m. Equation (8) represent the cost-efficiency of selected mitigation measures.

$$AP_m = \sum_m AR_{mi} * X_i \quad or \quad \sum_m AR_{mj} * H_j \tag{6}$$

$$PC_m = B_m - C_m \tag{7}$$

$$CE_m = PC_m / AP_m \tag{8}$$

Finally, the different measures are classified according to their cost-efficiency using the marginal abatement cost curve (MACC) method. A description of MACC and the main characteristics and details of implementation of the curve are presented in section 3.2.The MACC calculation are further developed by including the transaction costs. We follow the same steps described above, but now the costs of measures include both the implementation costs C_m and the transaction costs TC_m. Equation (9) define the measure costs MC_m given by the difference between the benefits B_m and costs of the measure m $(C_m + TC_m)$.

$$MC_m = B_m - (C_m + TC_m) \tag{9}$$

The transaction cost is the cost of implementation and enforcement mechanisms that ensure the adoption of mitigation measures by farmers and other design costs incurred because of the strategic behavior of farmers or other stakeholders and interest groups. The transaction costs are further discussed in section 3.3.

The estimation of the abatement potential of combined measures by taking into account the interaction between measures is challenging given the lack of technical and economic information when measures are taken simultaneously. Measures interaction should be included in the MACC analysis because of the changes in abatement potential and cost-efficiency from interaction. For example, optimizing nitrogen fertilization reduces the nitrogen fertilizer use and leaching, and therefore less abatement will be achieved by others measures reducing the efficacy of subsequent measures. Moran et al. and Schulte et al. [29, 30] evaluate the interaction between measures by adjusting their abatement potential when calculating the cumulative abatement. In this study, the abatement potential of combined measures is evaluated by ordering the sequence of measures, and then estimating the abatement potential and cost-efficiency of each measure by considering the order in the sequence and the interaction with previous measures. The order of measures is determined from the abatement potential of individual measures and the degree of applicability. The degree of applicability of measures come from the technical information provided by experts. The procedure generates two sequences of measures, one for crops and the other for livestock. The sequence of measures for crops is the following: M1. N input optimization; M2. Manure fertilization; M3. Minimum tillage; M4. Cover crops (arable crops); M5. Crop rotation; M6. Cover crops (woody crops); M7. Nitrification inhibitor; and M8. Irrigation modernization. The sequence of measures for livestock is the following: M1. Manure fertilization; M2. Protein diets; M3. Manure treatment plants; and M4. Fat additives.

In the mitigation scenarios for 2050, the projections for the agricultural sector include reductions in the irrigated area of barley and wheat, which switch to dryland. This is based on a 25% decline in water availability estimated by the Ebro Water Authority [22] for the period 2040-2070. In addition, an increase of 30% in swine numbers is considered given the excessive herd expansion in the region from 3.5 to 8 million heads between 2000 and 2018. Three scenarios are considered: business as usual with no mitigation measures engaged in the first scenario (S1); the second scenario includes only the most cost-efficient mitigation measures (S2); and the third scenario includes all mitigation measures (S3).

3.1. *Evaluation and selection of mitigation measures in agriculture and forestry*

There is a set of measures considered in the literature to mitigate GHG emissions in agriculture. Asgedom and Kebreab [31] assess various mitigation measures for crop and livestock production systems under different biophysical scenarios. They show that these measures have numerous economic and environmental benefits to reduce and avoid GHG emissions. Soil management is important to abate N_2O emissions and improve carbon sequestration by soils. Therefore, better soil management can substantially reduce GHG emissions and increase carbon sequestration in soils through the absorption of CO_2 by plants, increase the organic matter in soils, and adjust the nitrogen cycle. These improvements promote greater fertility and productivity, and enhanced soil biodiversity, while reducing erosion, runoff and pollution to the atmosphere and water media. Soil management practices include crop rotations [32], substitution of synthetic fertilizers by manure [33], use of efficient varieties with a larger mass of roots [34], cover crops [35], and reduced tillage or no-tillage [36]. Fertilization management is also a good alternative to reduce direct and indirect N_2O

emissions and the nitrogen loads from crops into water bodies. Those measures can improve atmosphere and water quality and increase nitrogen and water use efficiency.

The application of technical interventions and structural changes in livestock production could reduce emissions, increase carbon sequestration in pastures, and support sustainable livestock production. Livestock management measures include improving pasture, intensifying ruminants diets, and changing breeds [37]. In addition, the use of CH_4 inhibitors and fat in the diet of ruminants reduces CH_4 emissions from enteric fermentation [38]. Manure management measures include manure storage and manure treatment plants based in biological processes [39]. Forest management for carbon storage in forests and shrubs is another option to mitigate the effects of climate change, while enhancing the provision of ecosystem services. Forest management measures increase biomass and carbon in forest stands by modifying the thinning regime, the rotation period, and the harvesting operations. These strategies could improve soil protection, reduce the risk of fire, promote biological stability, and increase the value of products [40, 41].

This paper includes crop, livestock and forest measures. Crop measures include nitrogen input optimization, crop rotation with legumes, cover crops, efficient irrigation technologies, nitrification inhibitors, and minimum tillage. The measures for livestock are substitution of synthetic fertilizers by manure, manure treatment plants, use of fat additives in the diet of ruminants, and reduction of protein content in the diet of swine. In forestry, the focus is on management measures intended for carbon sequestration. The description of the selected measures is presented in Table 1.

3.2. *The MACC approach*

The marginal abatement cost curve (MACC) was first used by [42] to analyze mitigation policies in the US agriculture. Subsequently, it has been used in different studies at global, regional and national levels [43, 44, 45, 20, 21]. The MACC is a tool for mitigation policy analysis that brings a wide range of information about mitigation measures, and shows the potential of GHG abatement and the associated costs for different alternatives. This information reveals what are the most effective policy interventions in order to facilitate the exchange between scientific studies and policy decision-making.

The MACC is a figure with a series of discrete bars that represents the rising costs and the abatement of emissions from each mitigation measure. The width of each bar represents the reduction of GHG emissions ($MtCO_2e$), while the height of the bar shows the cost-efficiency of the measure (€/tCO_2e). The different measures are ordered according to their cost-efficiency, so that from left to right of the curve the cost-efficiency worsen as the accumulated abatement of measures increases and additional measures become more expensive. The figure has two parts, with the first part representing win-win measures that reduce emission and have negative costs, thus generating both economic and environmental benefits [51]. The second part of the figure represents measures with positive costs for stakeholders, and usually the cost burden falls on farmers. Therefore, the implementation of measures involves private costs for farmers, but generates environmental benefits for the whole society. Within the two parts, we can find measures reducing GHG emissions and saving money, and others with higher reductions but requiring costly investments. The MACC approach identifies the most efficient mitigation measures and can be compared to reference threshold costs per tCO_2e, such as the social cost of carbon from the OECD [26]. The MACC analysis is limited in different aspects: First, the choice of the emission categories considered in the analysis and the implementation costs included are determined by the researchers. Second, the MACC representation and cost-efficiencies are estimated at one point in time, but these estimates would be less accurate in the long run. MACC estimates become more uncertain in the future because of the charges in the implementation costs of current measures and from new measures embodying more advanced technologies. However, this analysis provides information to decision makers on the efficiency of measures that can be implemented in the short run.

Table 1. Description of selected measures.

Measures	Description
	Crop measures
N optimization	Efficient application of nitrogen fertilization according to the optimal requirements of each crop.
Crop rotation with legumes	Crop rotation increases soil carbon sequestration by 0.125 Mg/ha/year and reduces mineral fertilization by 50% [19, 46].
Cover crops	Cover crops increase carbon sequestration in the soil by 0.35 Mg C/ha/year in woody crops, and reduce GHG emissions by 10% in arable crops [47, 48].
Minimum tillage	Minimum tillage practices reduce GHG emissions by 0.47 tCO_2e/ha/year in cereals and 28% in corn [49].
Nitrification inhibitors	Adding inhibitors in the soil increases the efficiency of nitrogen use and reduces N_2O emissions by 30% [47].
Irrigation modernization	Replacing surface irrigation by sprinkler and drip systems increases the efficiency of water and nitrogen application.
	Livestock measures
Manure fertilization	Increasing the share of manure nitrogen fertilization from current 27% to 60%.
Fat additives	Adding 1% of fat reduces CH_4 emissions from enteric fermentation by 4% [38].
Manure treatment plants	Manure treatment plants reduce N_2O emissions by 60% using nitrification and denitrification processes in plants with 50,000 m^3/year capacity [50]).
Decrease of protein in the diet of swine	Adjusting the protein content in feeds reduces nitrogen excretion by 8.5%.
	Forest measures
Forest management	Adoption of forest management techniques for carbon sequestration.

In this study, the MACC is used to analyze mitigation measures in individual and combined forms. The effect of individual measures is analyzed without taking into account the interactions and dependencies among them, while combined measures are analyzed considering potential interactions between them. We also evaluate mitigation measures by including their transaction costs.

3.3. *Transaction costs and costs of measures*

In economics, transaction costs are defined as the cost incurred to complete economic exchanges or market transactions. The transaction costs literature was introduced by Coase in "The Nature of the Firm", indicating that is the cost of using the price mechanism. Other researchers have developed the theory of transaction costs: Williamson states that they are the costs of operating the economic system [52], and Cheung [53] indicates that transaction costs are all the costs from exchanges including the physical processes of production and transportation. Dahlman [54] states that transaction costs include research and information costs, negotiation and decision costs, and surveillance and execution costs. Transaction costs are also included into discussions about property rights, and on ecological and environmental policies. McCann [55] indicates that transaction costs should be considered in environmental policy design, and included in environmental and natural resources analysis. Garrick et al. [56] consider that transaction costs are useful to compare policy measures and those costs have to be included in the evaluation of the costs and benefits of policies. The estimation of transaction costs is challenging because of the different definitions and types of transaction costs. Liu and Shen [52] indicate also the difficulties in estimating the cost of non-market aspects such as transaction behaviors that differ according to culture and customs.

Many studies have measured the transaction costs of environmental policies. Howitt [57] shows that transaction costs represent 8% of the water purchase costs in California. McCann and Easter [58] report that transaction costs amount to 38% of the total costs of the United States Program of Technical Assistance for Agriculture. Mettepenningen et al. [59] analyze the transaction costs of European agri-environmental schemes and indicate that transaction costs are about 15% of the total cost of the policy and about 25% of the compensation payments. Coggan et al. [60] indicate that transaction costs of an environmental policy including both public and private transaction costs range from 20% to 50% of the total policy costs. Rorsted et al. [61] assess transaction costs of agricultural policies and demonstrate that transaction costs of environmental measures is about 20% of the total policy costs. In this paper, based on the previous literature we consider that transaction costs are 20% of the total cost of the measure. This is only an approximation because of the lack of information on the implementation and enforcement mechanisms in each mitigation measure to ensure their adoption by farmers, and the lack of information on the strategic behavior of farmers.

In this study, the costs of implementing measures and practices include the investment costs (seeds, machinery or equipment) and the costs of farm operations associated with each practice. In some cases, the costs are negative because the measures result in private benefits to farmers. Some examples are the costs saved from reductions in excessive fertilization, the increases in yields, or the substitution of synthetic by organic fertilization. The main sources of data used in the calculations of the costs are the regional statistical data published by the Spanish Ministry of Agriculture, literature reviews, and the outcomes from regional agro-economic models [62].

4. Results

4.1. *Assessment of agricultural GHG emissions in Aragon*

Agricultural activities generate important pollution loads from excessive nitrogen fertilization and intensive livestock. The consequence is the degradation of ecosystems by emissions of nitrates to water media and ammonia to the atmosphere, and global warming from emissions of N_2O and CH_4 to the atmosphere.

In Aragon, agricultural GHG emissions amount to 4.1 $MtCO_2e$, which represent 25% of the total emissions of the region. The emissions loads are located mainly in the districts of Monegros (14%), Cinco Villas (11%), La Litera (9%) and Hoya de Huesca (6%), due to the concentration of irrigated crops and swine production in these areas (Figure 2). The emissions come mainly from CH_4 and N_2O loads from manure management, which amount to 1.6 $MtCO_2e$ and 0.9 $MtCO_2e$, respectively. Direct and indirect emissions of N_2O from nitrogen fertilization of crops are close to 1 $MtCO_2e$, with 70% from direct emissions and 30% from indirect emissions of leaching and runoff. The largest share of fertilizer emissions come from irrigated crops (68%) and the rest from rainfed crops (32%), (Figure S1). Surface irrigation generates higher N_2O emissions than sprinkler and drip irrigation systems, with surface irrigation accounting for 56% of emissions, sprinkler 40%, and drip 4%. Emissions from enteric fermentation are 0.6 $MtCO_2e$ or 17% of agricultural emissions (Figure 3).

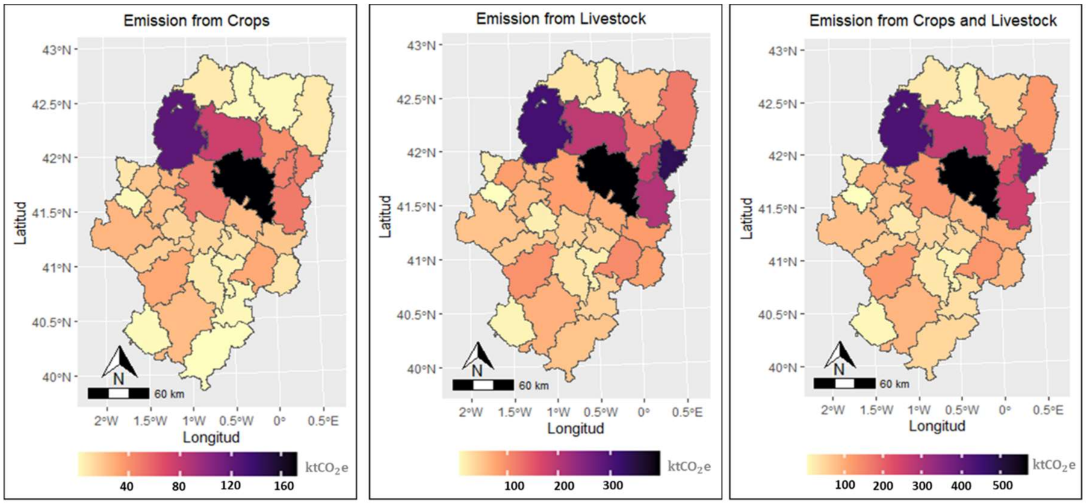

Figure 2. GHG emissions by county from crops, livestock, and the sum of crops and livestock.

Our results indicate that the GHG abatement potential from all individual measures (with and without transaction costs) is 3.45 $MtCO_2e$, which reduce current agricultural emissions by 84%. However if the interaction among measures is taken into account, the reduction in emissions is only 75%. The large abatement of GHG emissions provided by measures in both cases indicate the potential synergies between improving agricultural productivity and mitigating GHG emissions. Carbon sequestration measures such as forest management, cover crop, minimum tillage and crop rotation have the highest GHG abatement potential with reductions around 1.79 $MtCO_2e$ under both individual and combined measures. Measures that address livestock feed such as protein diet for swine and fat additives for ruminants have an abatement potential of about 0.65 $MtCO_2e$. N management measures like N optimization, manure fertilization, and nitrification inhibitors could reduce emissions by 1 $MtCO_2e$ with individual measures and 0.73 $MtCO_2e$ with combined measures (Fig. 3). The results suggest that some practices such as N optimization, Manure management, Crop rotation, and Protein diet have important win-win mitigation potential, because abatement is attained without additional costs for individual or combined measures. These measures increase both farmer's net income and the GHG abatement level. Cui et al. [63] prove that enhanced agricultural management practices reduce the use and pollution loads of nitrogen fertilizers while increasing farmers' income. Clark et al. [64] indicate that reducing GHG emissions from the food system can deliver additional benefits such as reducing nutrient and water pollution, decreasing land use change, and improving biodiversity outcomes.

4.2. *Mitigation measures assessment and transaction costs*

Figure 4 (a, b) shows the abatement potential and the cost-efficiency of individual measures with and without transaction costs. Results show that transaction costs worsens the cost-efficiency of measures without changing their abatement potential. Measures with negative abatement costs have significant abatement potential up to 2.9 $MtCO_2e$ for individual measures, although including transaction costs the abatement of measures that still have negative costs shrinks to 1.55 $MtCO_2e$. Win-win measures for mitigating emissions are N optimization, crop rotation, manure fertilization, and improvement of swine feed. Transaction costs worsens cost-efficiency, and some win-win measures such as minimum tillage and forest management become less attractive when including transaction costs.

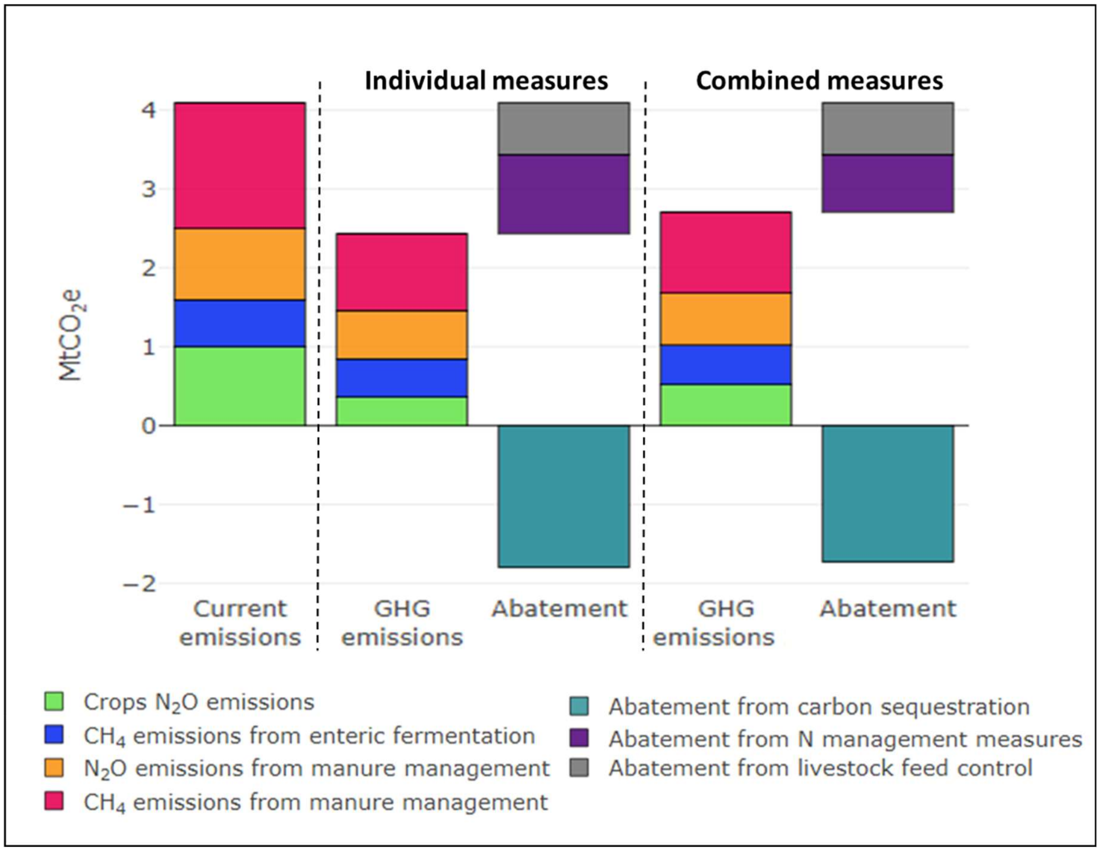

Figure 3. Agricultural GHG emissions and abatement under individual and combined measures. Individual measures are measures evaluated separately without considering interactions, and combined measures are evaluated taking into account their interactions.

Measures improving nitrogen efficiency and reducing N loads to the atmosphere and water media are evaluated. The measure N optimization provides a significant abatement of about 0.3 $MtCO_2e$ at negative costs in line with the findings by [45, 19, 20, 21]. This measure generates benefits to farmers that decrease their private costs while abating pollution and delivering environmental benefits. Manure fertilization substituting synthetic fertilization is another interesting measure achieving a 9% abatement at negative costs of -35 €/tCO_2e and -17 €/tCO_2e for the individual measure without and with transaction costs, respectively. Under this measure, the synthetic fertilization is reduced down to 76,000 tN, decreasing pollution into water media (-3,000 tNO_3-N) and the direct and indirect N_2O emissions (-218,000 and 97,000 tCO_2e, respectively). This measure has substantial interest in our study area, because of the availability of manure that could cover the nitrogen needs of most crops, especially in large irrigation districts [65]. Pellerin et al. [21] point out that manure fertilization in France reduces N_2O emissions with a negative cost of -74 €/tCO_2e. Albiac et al. [20] consider an increase in the proportion of organic fertilization up to 40% and 55% in Spain, which implies a cost-efficiency level of 75 and 140 €/tCO2e, respectively. The application of this measure requires organizing the cooperation between farmers cultivating crops and livestock producers.

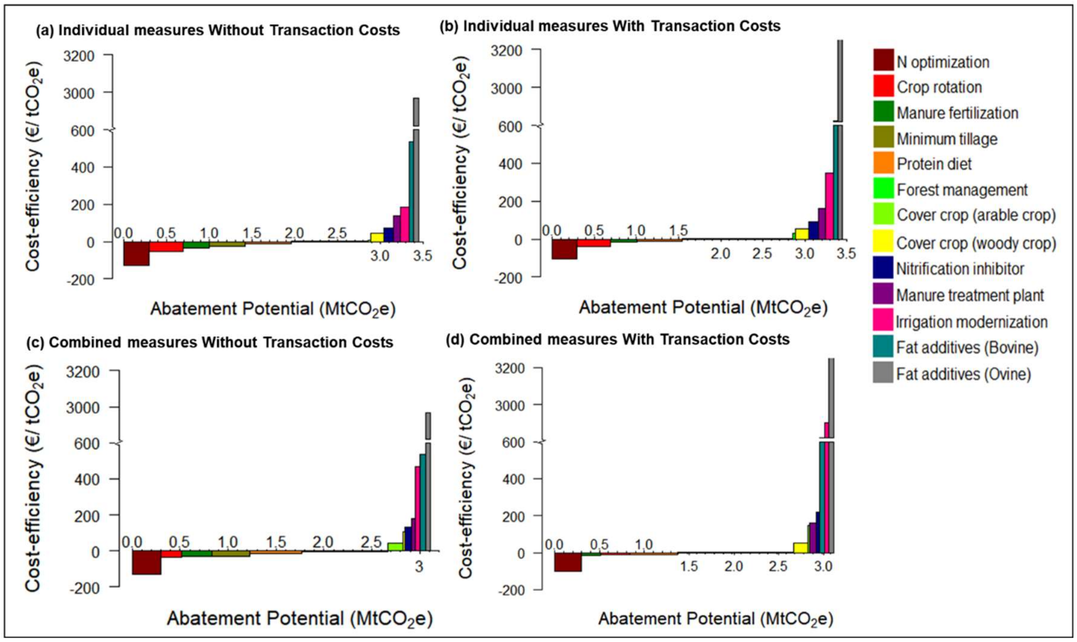

Figure 4. MACC of individual and combined measures.

Another measure considered is irrigation modernization, although advanced irrigation technologies require large investment and higher operating costs. Irrigation modernization improves the efficiency in the use of water and fertilizers, which reduce water use by 15% and fertilizer use by 13%. Albiac et al. [20] indicate also that irrigation modernization in Spain could reduce emissions by 2.1 MtCO2e with a cost-efficiency of 400 €/tCO2e. Nitrification inhibitors is also a type of measures that require expenses. This measure is quite efficient for maize, achieving an 84% reduction in N_2O but costs are significant. Pellerin et al. [21] point out that nitrification inhibitors has a cost-efficiency of 60 €/tCO2e for individual measures, which is very close to our estimate.

Measures that increase carbon sequestration in crops and forests are also analyzed, such as crop rotation, minimum tillage, cover crops, and forest management. Conniff [66] indicates that these measures increase carbon sinks with costs ranging from -35 to 88 €/tCO2e which are close to our results. Crop rotation with legumes is a measure with double benefits since it increases carbon sequestration and reduces N fertilization and N leaching. The abatement potential of crop rotation is 0.4 MtCO2e at negative cost of -53 €/tCO2e, although when transaction costs are considered, the cost-efficiency worsens to - 42 €/tCO2e. Minimum tillage is another interesting measure directed to increase carbon sequestration. This measure provides a significant abatement close to 0.4 MtCO2e with negative costs of -27 €/tCO2e, although transaction costs worsens the cost-efficiency of measure to 2 €/tCO2e. Macleod et al., Moran et al., and Sanchez et al. [44, 43, 19] indicate that minimum tillage has negative cost-efficiency. On the contrary, Pellerin et al. [21] indicate that minimum tillage in France has positive costs, although not significant (8 €/tCO2e).

Forest management to enhance carbon sequestration has an important role in mitigating climate change. This type of management increases carbon capture, with an abatement potential of 0.9 MtCO2e and costs at 0.5 €/tCO2e and -3.5 €/tCO2e when transaction costs are included or not, respectively. The negative cost is a consequence of the gains in income from enlarged wood sales.

Others measures assessed for reducing GHG emissions are manure treatment plants and improvements in the diet of animals, but results show that the costs of these measures are very high and require substantial investments. The implementation of these measures is rather difficult because they reduce the net income of farmers, and farmers will not implement them in the absence of public incentives.

The abatement potential of crop and livestock mitigation measures and forest carbon sequestration in each county of Aragon provide more detail about the efficiency of each mitigation measure in each location. Generally, the measures can be effective and viable in districts where agricultural activities are intense with large nonpoint pollution emissions (Figure S2).

4.3. *Effect of interaction between measures*

Results show that the abatement potential when all measures are combined is 3.11 MtCO$_2$e, which reduces current emissions by 75%. Combined measures with negative abatement costs have significant abatement potential, and reduce emissions to 2.6 MtCO$_2$e. The interaction between measures decreases the cumulative abatement potential by 10% compared to the abatement achieved with individual measures. In most cases, the interaction between measures reduces the abatement rate of subsequent measures and worsens the cost-efficiency, especially for measures with positive costs. For example, the abatement potential of irrigation modernization falls from 0.10 to 0.05 MtCO$_2$e and the cost-efficiency worsens from 184 €/tCO$_2$e to 470 €/tCO$_2$e without including transaction costs, and from 346 €/tCO$_2$e to 802 €/tCO$_2$e including transaction costs. Also the abatement potential of nitrification inhibitors decreases from 0.11 to 0.04 and the cost-efficiency worsens from 74 €/tCO$_2$e to 182 €/tCO$_2$e without transaction costs, and from 90 €/tCO$_2$e to 220 €/tCO$_2$e including transaction costs. (Figure 4 (c, d)). Some measures such as forest management or fat additives for ruminants do not have interactions with previous measures and thus maintain their abatement potential and cost-efficiency. Macleod et al [44] indicate that the large discrepancies between individual and combined measures indicate that interactions are important in developing MACC.

4.4. *Mitigation policy scenarios*

Climate change entails large uncertainties for the future development and sustainability of the agricultural sector. In a globalized world, mitigation and adaptation measures require coordination of countries and sectors, while ensuring at the same time food security for the human population. Mitigation scenarios show the consequence of policy decisions on the agricultural GHG emissions in the future, linking the balance of GHG emissions to each policy choice. Future agricultural developments up to 2050 include the increase of swineherds and the reduction of water available for irrigation, with some barley and wheat production changing from irrigated to dryland. These future developments of agriculture in Aragon would increase emissions by 26% in the next 30 years compared to the current situation, with emissions reaching 5.2 MtCO$_2$e in the business as usual scenario (S1). This increase is driven by the rise of GHG emissions from manure management (Figure 5 (a)).

Under the scenario of implementation of the more viable and efficient measures (S2), the individual measures reduce GHG emissions only by 1 MtCO$_2$e down to 4.2 MtCO$_2$e in 2050 with private benefits of 60 M€ to farmers. The consideration of transaction costs reduces these benefits of farmers to 34 M€. Taking into account interactions, the combination of measures reduces emissions only by 0.9 MtCO$_2$e with private benefits at 33 M€ or 56 M€ by including and not including transaction costs, respectively

(Table S1). Positive private benefits will facilitate the smooth implementation of measures and the support from farmers. This scenario allows to dampen down current GHG emissions up to 2050 under both individual and combined measures. However, the stabilization of GHG emissions is not a very ambitious alternative to confront the threat of climate change, conserve natural resources, and protect the environment (Figure 5 (b, c)).

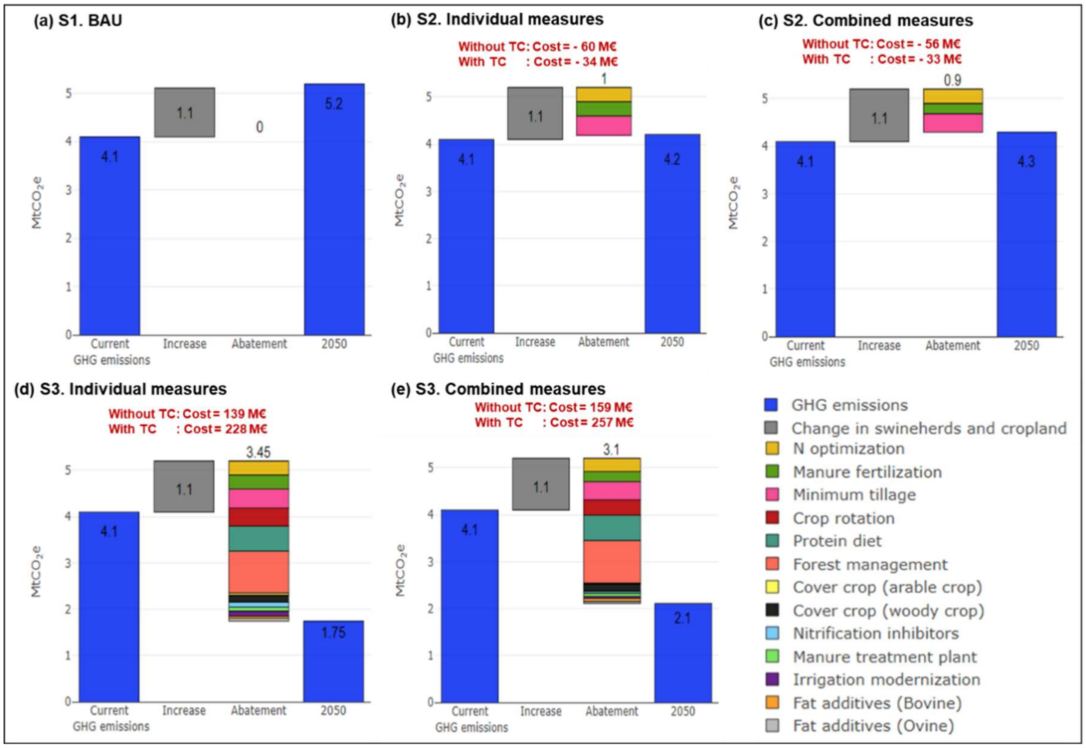

Figure 5. Mitigation policy scenarios in the 2050 horizon. The figure shows the current and the 2050 emissions under the different scenarios. "Increase" refers to the increase of emissions in 2050 from changes in swineherds and cropland, and "Abatement" refers to the reduction of emissions from measures. BAU is the Business As Usual scenario, and TC are transaction costs.

The implementation of all measures (S3) provides a significant abatement of 3.4 $MtCO_2e$ in agricultural emissions in the 2050 horizon, at positive cost of 139 M€ without transaction costs and 228 M€ including transaction costs. When interactions are accounted for, abatement diminishes to 3.1 $MtCO_2e$ with a positive cost of 159 M€ without transaction costs and 257 M€ including transaction costs (Figure 5 (d, e); Table S2). In order to implement mitigation measures, the cooperation between agents and interest groups is needed for collective action. Albiac et al. [67] point out that the sustainable management of natural resources and the protection of the environment require a sufficient degree of collective action and cooperation among interest groups. Jiao et al. [68] emphasis the urgency of sharing knowledge and efforts among scientists, farmers, and institutions. The cooperation is an essential ingredient for the sustainable management of natural resources and the agricultural sector, the protection of ecosystems, and the well-being of future generations.

5. Conclusions

This study analyzes a series of mitigation measures in agriculture, giving a first estimation of the potential of individual and combined mitigation measures for agriculture the region of Aragon (Spain). These mitigation measures rely on information from the biophysical processes underlying crop, livestock, and forest systems, in order to reduce GHG emissions and combat climate change. Comprehensive nutrient management requires knowledge on the sources and sinks of the nitrogen cycle, for a correct assessment of measures reducing GHG emissions to the atmosphere and pollution to water media from crops and manure leaching and runoff. The measures are assessed using the MACC approach, which is an instrument supporting the policy analysis of mitigation measures.

The results of this study show that the abatement potential from all individual measures is 3.45 $MtCO_2e$, which reduce current agricultural emissions by 84%. The abatement potential of the combined measures decreases to 3.11 $MtCO_2e$, because interaction among measures reduces their abatement potential and worsens their cost-efficiency. The results show also that the most efficient mitigation measures are optimization of nitrogen fertilization, manure substitution of synthetic fertilizers, crop rotation, and reduction of protein content in the diet of swine, which achieve substantial abatement with negative costs (i.e., win-win measures). Transaction costs are included in the estimation of MACC, providing a better ranking of measures and a more accurate estimation of implementation and enforcement costs. The consideration of both transaction costs and interactions between measures in developing MACC contributes to a better decision making on the choice of the appropriate mix of measures.

The projection of the agricultural sector developments in Aragon into the future indicates that the volume of emissions could reach 5.2 $MtCO_2e$ in the 2050 without mitigation. The implementation of mitigation measures would require an effective deployment and uptake by farmers, and their active cooperation in order to reduce GHG emissions. The implementation of measures depends on the objectives of decision-makers, but also on the availability of biophysical and economic information. The design of measures must take into account local characteristics regarding the economic and environmental effects, and social acceptability. Policies have to be legitimate because successful implementation cannot be achieved without the support of stakeholders. Cooperation between farmers, stakeholders, and interest groups is needed for a reasonable allocation of resources and for achieving significant nonpoint pollution abatement efforts.

This study could be further advanced by including a detailed analysis of the viability of mitigation measures. The effort involves setting up the mechanisms to ensure the adoption and enforcement of mitigation measures by farmers, taking into account the strategic behavior of the interest groups. Understanding the strategic behavior of farmers and others stakeholders is important to advance the required cooperation for successful mitigation.

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