



Food and Agriculture
Organization of the
United Nations

Making public investments Paris Agreement-aligned in a cost-effective way

Calculating marginal abatement cost curves
for agricultural investments

FAO AGRICULTURAL DEVELOPMENT ECONOMICS
WORKING PAPER 24-02

ISSN 2521-1838



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**Calculating marginal abatement cost curves
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Joanna Ilicic

Lorenzo Maestriperi

Greta Dobrovich

Adriana Ignaciuk

Alma Rottem

Food and Agriculture Organization of the United Nations

Rome, 2024

Required citation:

Ilicic, J., Maestriperri, L., Dobrovich, G., Ignaciuk, A. & Rottem, A. 2024. *Making public investments Paris Agreement-aligned in a cost-effective way – Calculating marginal abatement cost curves for agricultural investments*. FAO Agricultural Development Economics Working Paper, 24-02. Rome, FAO. <https://doi.org/10.4060/cd0779en>

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ISSN 2664-5785 [Print]

ISSN 2521-1838 [Online]

ISBN 978-92-5-138781-8

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Abstract

This paper proposes a novel methodology for calculating marginal abatement cost curves (MACCs) for public finance in agriculture using granular data on specific activities from investment projects. The proposed MACCs target public investment decision makers from the international and national financing institutions, as well as governments. The methodology is based on information obtained from agricultural projects implemented by international funding institutions (IFIs) and carbon accounting appraisals conducted using the Food and Agriculture Organization of the United Nations (FAO) EX-Ante Carbon-balance Tool (EX-ACT). The curves are estimated through a bottom-up approach, in which actual data on mitigation potential of agricultural investments and their associated costs are used to derive the cost-effectiveness of individual agricultural activities. The resulting curves illustrate the relationship between the cost of each individual activity and their individual mitigation potential helping decision makers to identify how to achieve best results at lowest cost. The application of the methodology is demonstrated using a sample portfolio of projects under World Bank's Global Agriculture and Food Security Program (GAFSP).

Isolating the contribution of individual practices and highlighting their contextual cost-efficiency is a key factor in investment decision making for private and public entities aligning with the global climate targets. Given the complexity of estimating real costs, bottom-up MACCs offer a precious reference for evaluating activities' abatement potential and supporting decision-making processes of policymakers and investors interested in efficient and climate-friendly investments.

Keywords: climate change mitigation, agricultural investments, cost-effective investments, marginal abatement cost curves.

JEL codes: Q14, Q18, Q51, Q54, O13.

Acknowledgements

The authors would like to thank colleagues from Economic and Policy Analysis of Climate Change Team in the FAO Agrifood Economics and Policy Division (ESA) for their valuable contributions. In particular, Sravya Mamidanna provided useful comments and observations that helped finalize the work. Aidanek Orozalieva ensured the document meets the editorial standards.

The authors recognize the instrumental role of the World Bank's GAFSP Coordination Unit in providing access to the necessary data for conducting the case study.

The authors would also like to acknowledge Stephany Roe for the detailed explanations of the database used to derive the cost allocation key; they helped to validate the approach the paper proposes to disaggregate the costs when necessary.

The authors are thankful to the ESA Working Paper Review Board who provided very useful insights; the paper highly benefitted and improved.

Finally, the authors would like to thank Daniela Verona (ESA, FAO) for her editorial and layout support, as well as publishing coordination.

1 Introduction

Agricultural investments have a key role to play in the fight against climate change by encouraging activities that reduce greenhouse gas (GHG) emissions or sequester carbon. Harnessing this potential is key for the success of every project to ensure that productivity threats stemming from climate change are reduced, and global warming is brought to manageable levels. The agriculture, forestry and other land use (AFOLU) sector represents almost one-quarter of all anthropogenic GHG emissions generated annually (IPCC, 2022). Yet, it is also a victim of the changing climate, mostly through threats to agricultural production and productivity, land degradation and weakening of the general ecosystem resilience.

Many countries and financing institutions are committed to align their investments with the Paris Agreement; but making sure that this happens, implies finding cost-effective solutions tailored to the specific biophysical and socioeconomic conditions of the investment areas. The mitigation potential of the AFOLU sector lies between 8 and 14 GtCO₂-eq mitigated per year between 2020 and 2050, and almost half of this could be achieved by investing less than USD 20/tCO₂-eq (IPCC, 2022).¹ However, while a wide a range of available mitigation measures exists, it is not always straightforward to identify which measure is the most cost-effective within the sector to maximize the climate benefits under given financial constraints. Carbon sequestration and GHG emissions reduction in the AFOLU sector are highly context-specific, and a one-size-fits-all strategy would not allow for achieving significant climate benefits in a cost-efficient way. Climate and soil conditions, institutional capacities, and socioeconomic characteristics all play a crucial role in determining the cost and feasibility of implementing a specific agriculture measure. For instance, tropical countries retain greater cost-effective potentials in AFOLU than temperate and boreal ones because of the vegetation and soil that this climate entails (Griscom *et al.*, 2020); less carbon-intensive farm machinery has the most significant cost-effective potential in advanced economies (McKinsey & Company, 2020), but would likely backfire in many developing countries where access to technology and know-how comes with a higher implementation cost (IPCC, 2022; Roe, 2021). Poorly planned activities may have adverse effects on medium to long-term food security and livelihoods, and in effect waste the invested financial resources (Smith *et al.*, 2020).

A growing effort is being made at the global level to allow decision-makers to discern between more cost-effective and less cost-effective mitigation options for their highly context-specific agricultural² sector. The most popular approach to link mitigation potentials and costs at a country and sectorial level is through marginal abatement cost curves (MACCs). MACCs visualize the relationship between the cost associated with GHG mitigation measures and the abatement potential of each measure in a form of a curve. The curve ranks the measures according to their relative cost-efficiency, that is, the relative cost of achieving a certain amount of GHG mitigation. The MACCs literature is still lagging in the agriculture sector. The context specificity of agriculture measures and the lack of precise and unequivocal data, challenge the estimation of these curves that often do not have enough granularity.

To fill this gap, this paper proposes a methodology for calculating MACCs for public finance in agriculture using granular data on specific activities from investment projects. The proposed

¹ FAOSTAT estimates that in 2020, AFOLU was responsible for 7.5 GtCO₂-eq of GHG emissions (FAO, 2024).

² Agricultural sector is understood broadly, encompassing AFOLU but also use of inputs, agricultural infrastructure, fisheries, aquaculture, and management of coastal zones.

MACCs target public investment decision makers from the international and national financing institutions, as well as governments. The methodology is based on information obtained from agricultural projects implemented by international funding institutions (IFIs) and carbon accounting appraisals conducted using the Food and Agriculture Organization of the United Nations (FAO) EX-Ante Carbon-balance Tool (EX-ACT) (available at <https://www.fao.org/in-action/epic/ex-act-tool/suite-of-tools/ex-act>). The curves are estimated through a bottom-up approach, in which actual data on mitigation potential of agricultural investments and their associated costs are used to derive the cost-effectiveness of individual agricultural activities.

The paper starts with defining what constitutes a MACC and how MACCs are calculated in the existing literature, including for the agricultural sector (Section 2). Next, it outlines the proposed methodology and discusses the challenges related to collecting adequate information (Section 3). A case study using a sample portfolio of World Bank's GAFSP projects illustrates applicability of the methodology to any type of agricultural investment, whether specifically targeting climate objectives or not (Section 4). The paper also discusses applicability of the methodology and some of the associated limitations (Section 5). The final section concludes (Section 6).

2 Marginal abatement cost curves

2.1 What is a marginal abatement cost curve?

A marginal abatement cost curve estimates the costs of reducing emissions within a fixed target and in a certain time horizon (Nocera and Cavallaro, 2012). It plots the relationship between the marginal cost of GHG emissions abatement and the amount of GHG emissions abated. Usually, the volume of GHG emissions is expressed in terms of tonnes of carbon dioxide equivalent (tCO₂-eq) abated (Morris, Paltsev and Reilly, 2012; McKinsey & Company, 2020). MACCs are often used in decision-making processes as they provide a clear and simple way of describing the cost-effectiveness of different mitigation measures.

Although approaches for calculating MACCs vary significantly, they fall under two main methodological approaches:

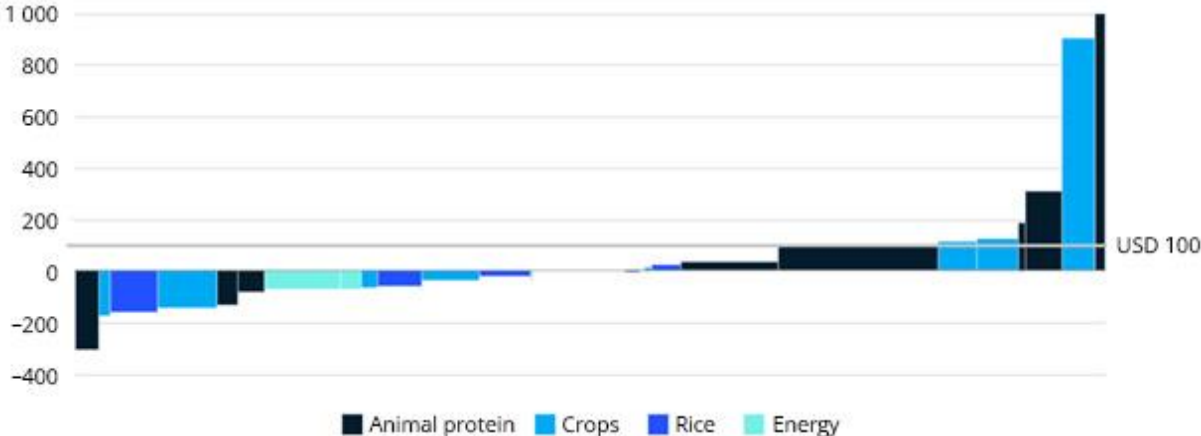
- The first is a top-down approach, starting from general economic considerations to draw conclusions on the potential mitigation achievements of various sectoral activities.
- The second is a bottom-up approach, focusing on the cost-effectiveness of individual measures to induct general recommendations on climate change mitigation potential at different levels of aggregation.

While the former is mainly used to assess macroeconomic and fiscal implications of environmental policy, the latter is considered the most appropriate to conduct country-level analyses (Stern, 2009; Roe *et al.*, 2021). Consequently, the two approaches are not alternative, but rather complementary, depending on the aim of the research.

MACCs are usually plotted as a histogram (McKinsey & Company, 2020, 2023; Eory *et al.*, 2018), ordering individual activities from the most cost-efficient to the least cost-efficient to guide policy design. Figure 1 helps to visualize these characteristics, where one can see, from left to right, the least to the most expensive methods to abate emissions. MACCs allow to identify the cost-efficiency of individual mitigation measures through a “step function” (Kesicki, 2012):

- The width of each bar represents the magnitude of emissions reduced compared to a baseline scenario or, in other words, the abatement associated with each individual measure (wider bars mean more emissions reduced).
- The height of the bar shows the actual cost-effectiveness of that abatement, which usually corresponds to the cost associated with the mitigation of one tCO₂-eq (higher bars means costlier abatement).
- The area of each bar in the histogram represents the total cost of the respective mitigation measure.

Figure 1. The marginal abatement cost curves for agriculture by McKinsey & Company (2023)



Source: Based on McKinsey & Company. 2023. *The agricultural transition: Building a sustainable future*. New York, USA. <https://www.mckinsey.com/industries/agriculture/our-insights/the-agricultural-transition-building-a-sustainable-future>

2.2 Marginal abatement cost curves for the agricultural sector

The evaluation of the potential abatement of mitigation measures for an agricultural project requires two main data points:

- the costs associated with the measure, to quantify its value in monetary terms;
- the GHG fluxes of implementing the measure compared to a reference emissions scenario.³

The combination of environmental and economic data to construct a MACC is not unique to the agricultural sector and is based on complex analyses of mitigation activities that may extend well beyond the information available in conventional project documentations. Constructing a MACC for agricultural projects would ideally require close communication between researchers and stakeholders to understand the practices used and the associated costs.

Notwithstanding their limitations, literature holds several attempts of estimating MACCs for the agricultural sector throughout the world, including MacLeod *et al.* (2010), Moran *et al.* (2010); Griscom *et al.* (2017); Eory *et al.* (2018); Griscom *et al.* (2020); McKinsey & Company (2020, 2023); Roe *et al.* (2021); and most recently the IPCC (2022). MACCs are an increasingly useful tool for policymakers and investors interested in efficient and climate-friendly investments. Isolating the contribution of individual practices and highlighting their contextual cost-efficiency is a key factor in investment decision making for private and public entities aligning with the global climate targets. Given the complexity of estimating real costs, bottom-up MACCs can represent a precious reference for evaluating activities' abatement potential. They have the strength of being simple enough to compare abatement potentials at all levels of the economy: countries, sectors and farms. Referring to these methodologies, Stern, 2009, admits that using

³ The reference scenario represents the most “realistic and credible land-use scenarios that would have occurred on the land within the proposed project boundary in the absence of the [...] project activity [...] taking into account relevant national and/or sectoral policies and circumstances, such as historical land uses, practices and economic trends” (CDM, 2007, p.3).

actual examples of activities, bottom-up MACCs offer easier to interpret estimates of cost-effective mitigation measures than those provided through top-down approaches. Listing options from the least to the most expensive, these curves offer valuable insights into the type of regulation that may be advisable in a specific sector. Consequently, bottom-up methodologies have become increasingly popular in recent years (see, for example, MacLeod *et al.* [2010]; Eory *et al.* [2018]; McKinsey & Company [2020, 2023]).

Considering that much of the current literature applying MACCs to the agricultural sector focuses on developed countries such as the USA, the UK, and EU countries (MacLeod *et al.* [2010]; Moran *et al.* [2010]; Eory *et al.* [2018]) developing MACCs that extend such research to other regions is of primary relevance to support developing sustainable agri-food systems worldwide. Among major attempts to provide a country-level global overview on agriculture, the studies from Griscom *et al.* (2017, 2020) and Roe *et al.* (2021) stand out. While the authors do not directly calculate MACCs, but rather gather and adapt/harmonize data from other work in the field, these studies provide the greatest attempt to offer a comprehensive view of costs and mitigation potential of a set of agriculture mitigation measures by country.

Griscom *et al.* (2017) explore the cost-effectiveness⁴ of 20 natural climate solutions and show the distribution of mitigation opportunities by country. However, as costs are derived from global MACCs, it is not possible to provide country-level disaggregation: costs and countries' mitigation potentials remain unlinked. A step forward is taken in a subsequent paper. Griscom *et al.* (2020) gather data from several biophysical studies and assess the cost-effectiveness of natural climate solutions in tropical countries. The authors point out the significance of climate conditions in the determination of costs and reiterate the need for country-level appraisals to support planning in nationally determined contributions (NDCs). Unfortunately, data gaps prevent them from replicating the analysis in other climates. Roe *et al.* (2021) review, merge and update 25 databases from ten different studies and build the most comprehensive database on cost-effective mitigation actions by country. However, although the authors perform a remarkable job in harmonizing data when working with different methodologies, issues such as double counting cannot be excluded. A robust methodology consistently estimating agriculture cost-effectiveness is still lacking. This paper contributes to bridging this gap with the approach based on actual data on mitigation potential of wide range of agricultural activities and their associated investment costs.

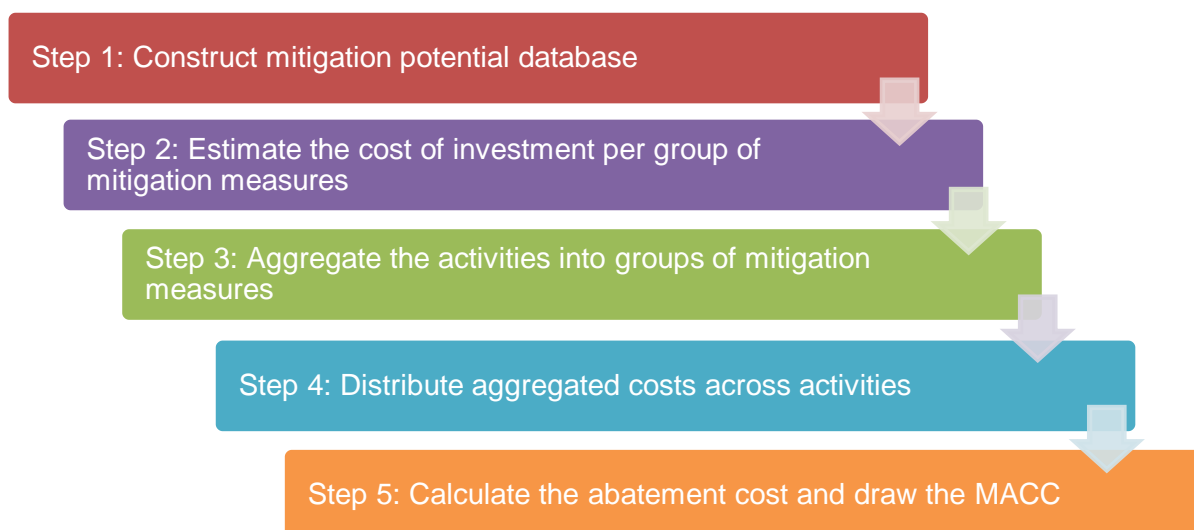
⁴ Griscom *et al.* (2017) define cost-effective mitigation as marginal abatement cost up to USD 100 MgCO₂-eq by 2030.

3 Methodology for calculating marginal abatement cost curves in the context of public investments in agriculture

Drawing on actual data from investments in agriculture, this paper proposes a unique methodology to calculate bottom-up MACCs from public investments in the agricultural sector. The methodology builds on information on activity costs extracted from project documents and mitigation potentials linked to each activity as appraised using the EX-ACT. The main benefit of this methodology is that it ensures complete geographical and climatic representation as it allows to calculate MACCs by location, climate, moisture and soil type. As a result, it offers a strong base to build tailored recommendations and steer policy and investment towards sustainable development.

The proposed methodology involves five steps illustrated in Figure 2 and described in more detailed below.

Figure 2. The five steps to calculate the marginal abatement cost curves (MACCs) for mitigation activities in agriculture



Source: Authors' own elaboration.

Step 1: Construct a mitigation potential database

The mitigation potential database builds on the wealth of climate mitigation effects appraisals for various projects using the EX-ACT.

The EX-ACT is widely used for estimating and tracking the effects of agricultural investments and policies on GHG emission levels. It mainly draws on the Intergovernmental Panel on Climate Change (IPCC)'s Guidelines for National GHG Inventories (IPCC, 2006) and takes into account activities that impact GHG fluxes (CO₂, CH₄ and N₂O) or changes in carbon stocks (above ground biomass, below-ground biomass, soil, litter and deadwood) to provide the carbon balance expressed in tonnes of CO₂-equivalent. It covers a wide range of activities, including deforestation, afforestation, other land use changes, annual, perennial and flooded cropland management, grassland and livestock management, forest degradation management, wetland management, fisheries and aquaculture, and finally inputs, energy and infrastructure. More details are provided in Box 1.

Box 1. The EX-Ante Carbon-balance Tool (EX-ACT)

EX-ACT is a free tool developed by FAO, providing its users a consistent way of estimating and tracking the impact of agricultural* investments and policies on GHG emission levels. The EX-ACT methodology mostly draws on the IPCC's Guidelines for National GHG Inventories (IPCC, 2006), their Wetland supplement (IPCC, 2014) and their refinement (IPCC, 2019), complemented with other scientific sources.

The tool takes into account activities (detailed in the different modules and sub-modules of the tool), that impact GHG fluxes (CO₂, CH₄ and N₂O) or changes in carbon stocks (above ground biomass, below-ground biomass, soil, litter and deadwood) to derive the carbon balance expressed in tonnes of CO₂-equivalent (relative to a reference situation).

Building a carbon balance implies constructing a reference scenario to quantify accurately the emissions reduced (increased) or sequestered (released) as a result of implementing an agricultural activity. The reference scenario may or may not coincide with the situation at the start of project implementation.

A positive carbon-balance entails an increase in GHG emissions compared to a reference scenario, while a negative carbon-balance indicates that there is carbon-sequestration or GHG emission reduction. The time span for calculating a carbon balance is usually assumed equal to twenty years, following the IPCC (2019b) recommendations, to ensure that biophysical processes that lead to changes in soil organic carbon content have taken place.**

Activities covered by the EX-ACT include deforestation, afforestation, other land use changes, annual, perennial and flooded cropland management, grassland and livestock management, forest degradation management, coastal and inland wetland management, fisheries and aquaculture, on-farm inputs, energy and infrastructure.

The tool, now in its ninth version, is always encompassing more data sources and agricultural activities as scientific evidence evolves, allowing for progressively improving estimates of GHG fluxes in the AFOLU sector.

The MACCs methodology included in the paper is based on assessments completed using the eight version of the tool. As the database is enriched with more recent case studies, it is likely that the use of a more updated version will influence the provisional results of this first endeavour.

Notes: * Agriculture, forestry and other land use (AFOLU), fisheries and aquaculture, on-farm input, energy, irrigation and infrastructure. ** More on this point can be found in following sections of this paper and in Chapter 2 of IPCC (2006).

Source: Authors' own elaboration.

After each project is analysed, crucial data on each agricultural project is identified and isolated. These include the type of project, main financing entities, budget and beneficiaries, as well as the progression stage of its implementation. EX-ACT assessments are performed at different stages of implementation, i.e. *ex ante*, mid-term, *ex post*, and the database allows to keep track of the costs actually incurred in and mitigation really achieved. Further, EX-ACT calculates the carbon-balance by project activity. Therefore, after an assessment is performed, the mitigation potential of specific agricultural interventions can be easily isolated. As the carbon balance is calculated depending on the projects' specific location, climate, moisture regime, soil type, and implementation and capitalization time, these data are also collected in the database.

Considering the above, the use of EX-ACT offers a unique opportunity to calculate MACCs according to specific agricultural activities while accounting for geophysical dimensions. The database is continuously updated as new project assessments are carried out by FAO climate mitigation experts, allowing for a progressively increasing the amount of information to be processed and fed into the MACCs.

Step 2: Estimate cost of investment per mitigation measure

Following CDC Climat research (CDC Climat, 2014), this paper defines the cost of abatement as the monetary value of the investment reported and budgeted in each project. Costs included aim at the most realistic representation of actual financial resources committed by investor (public or private) to implement a specific mitigation activity. In this sense, all costs that can directly be associated with a mitigation measure are considered in the accounting, including training, project management and other transaction costs that can directly be associated with an activity according to the available reports. Any co-benefits (or costs) of beneficiaries are not considered. As a result, no mitigation option entails negative costs: the actual investment costs listed in the project budgets for implementing each measure are always positive.

Data on costs of investments used to derive the MACCs are sourced from project-related documentation, including project documents, project cost tables and economic and financial analyses (EFAs). The choice of one or more sources of information for the accounting of costs depends on the stage of implementation of the project and data accessibility:

- Project documents often include cost splits at the level of project components. These can be relevant at all stages of implementation but usually lack the necessary granularity for the direct association of mitigation measures to their costs.
- EFAs represent the primary source of cost information for projects that are at design stage or in implementation at the time of the mitigation appraisal. They include an overview of necessary expenses for the implementation of each mitigation with a high level of detail and can also be partially contained in project document annexes.
- Cost tables usually become available at project closure, as they report actual expenditure as incurred by the financing institution for the accomplishment of targets actually achieved.

The costs correspond to the value of the investment of the financing institution. This has two direct implications.

First, all expenses covered by the financing institutions that can be linked to a mitigation measure are accounted for: this includes direct material costs, as well as transaction costs and other costs, to the extent that they are associated with the measure in project-related documentation. This is a crucial advantage of this approach. Usually, bottom-up MACCs have the main limitation of disregarding transaction costs like those arising from agency regulatory approval and administration capacities (McKinsey & Company, 2009; Gillingham and Stock, 2018). However, the relevance of transaction costs can be significant: investigating the costs of 12 agricultural projects in Norway, Rorsted *et al.* (2007) find out that transaction costs could be responsible for about 20 percent of a project's total cost. Similarly, Coggan *et al.* (2010) highlight that this percentage could vary between 25 percent and 50 percent on a case-by-case basis. Transaction costs are also closely linked to the size of the project and its location, as for example, costs in different countries require a different risk premium. Although the proposed methodology does not account for all hidden costs, for instance excluding the costs

associated with the project management at the design stage as those are not directly available in the project documentation, it still covers all those costs that are explicitly stated in the project documents and that are directly associated with the implementation of mitigation measures.

Second, and as mentioned above, any other additional cost or benefit that may be induced by the investment is excluded from the accounting. For example, if a beneficiary of investment – a farmer who receives funding to engage in agroforestry activities – incurs costs related to land conversion, this will not be considered. Similarly, any benefits – such as income from sale of perennial crops – will not be considered. By focusing solely on public investment, this method allows to remove a great deal of uncertainties related to the calculation of actual costs of implementation for each measure. Further, it delivers very clear information to the investors (public or private) by telling them how much they need to invest to attain a certain mitigation potential and supporting them in identifying the most cost-effective options.

Given the variability of information sources, it is not possible to elaborate a standard approach for cost isolation and attribution. Each project requires tailored analysis of costs according to the implementation stage, the availability of data and the possibility to interact with the implementing team. The latter element represents a key asset in ensuring that costs identified through files accurately reflect the reality of the implementation of the project at a given stage (*ex ante*, mid-term and *ex post*).⁵ Every cost attribution requires a careful approach and cross checking of reliability of estimates may be necessary.

Step 3: Aggregate the activities into uniquely identifiable groups of mitigation measures

The EX-ACT allows to assess the mitigation potential at a disaggregated level. However, depending on the cost information availability, activities performed under each project and listed in the database may need to be aggregated into pre-determined and uniquely identifiable groups of mitigation measures.

The aggregation of measures allows for a normalization of activities through a categorization that allows for a comparison across time and space. The aggregation of activities is not a necessary step into the construction of a MACC but may be favoured in situations of scarce information or limited data points. The wider the categories in which the mitigation measures are grouped, the less granular the result curves will be.

The considered list of measures corresponds to the main sub-modules in EX-ACT and three layers of disaggregation (Table 1). At this stage of the methodology, the grouping is still performed per project and may vary across project portfolio. However, the final database allows for bringing all to higher level of aggregations to ensure comparability across the various portfolios of projects.

It is important to note that only mitigation options are included in the measurement groupings. Activities generating GHG emissions have been automatically excluded from the dataset, unless they are coupled with other measures generating an overall mitigation. As an example, implementing irrigation on crops entails positive (linked to the installation of the systems) and negative GHG fluxes (generated by the higher rate of carbon sequestration in the cropland). If the sum of such fluxes results in a negative GHG flux, the activity is included in the list.

⁵ The final database records the implementation stage of each project included in the database.

This approach allows to focus specifically on activities engendering a positive impact on the environment.

Table 1. Groups of measures considered for calculating marginal abatement cost curves

Measure	Layer 1	Layer 2	Layer 3	
Land use change improvements	Avoided deforestation	Avoided deforestation	Avoided deforestation	
	Afforestation/reforestation	Afforestation/reforestation	Afforestation/reforestation	
	Other land use changes	Other land-use change improvements	Land restoration Productivity improvement	
Crop management improvement	Annual crops improvement	Improvement of annual crops	Tillage reduction	
			Irrigation	
			Manure application	
		Change in residue management		
		Improvement of annual crops converted from other land uses	Tillage reduction	
			Irrigation	
	Manure application			
	Perennial crops improvement	Improvement of perennial/tree crops	Change in residue management	
			Change in agroforestry system	
			Improvement of agroforestry system	
			Improvement of perennial/tree crops converted from other land uses	Tillage reduction
				Irrigation
				Manure application
		Change in residue management		
		Change in agroforestry system		
Improvement of agroforestry system				
Flooded rice improvement		Improvement of flooded rice fields	Change in seasons or cropping days	
			Change in water management before cultivation	
			Change in water management during cultivation	

Measure	Layer 1	Layer 2	Layer 3
			Change in residue management
		Improvement of flooded rice fields converted from other land uses	Change in seasons or cropping days
			Change in water management before cultivation
			Change in water management during cultivation
			Change in residue management
Grassland improvement	Grassland improvement	Improvement of grasslands	Irrigation
			Land restoration
		Improvement of grassland converted from other land uses	Irrigation
			Land restoration
Livestock improvement	Livestock improvement	Improvement of livestock	Feeding improvement
			Breeding improvement
			Manure management
Forest degradation management	Forest degradation management	Forest degradation management	Avoidance of forest degradation
			Forest restoration
			Forest fire management
Improvement of fishing and aquaculture	Improvement of fishing and aquaculture	Improvement of fishing and aquaculture	Improvements in fuel use management
			Change in fishing gear
			Change in species targeted
Inland wetland management	Inland wetland management	Inland wetland management	Biomass restoration
			Avoidance of biomass degradation
			Management of the water table
			Fire management
			Management of peat extraction
Coastal wetland restoration	Coastal wetland restoration	Coastal wetland restoration	Biomass restoration
			Soil restoration

Source: Authors' own elaboration.

Step 4: Distribute aggregated costs across activities

Available documentation does not always include sufficiently detailed information to disaggregate costs according to the mitigation measures identified and activities may need to be grouped together into wider categories. Sometimes, it is entirely impossible to connect individual project activities (or groups of measures) to costs. In these cases, the project should be excluded to reduce statistical noise surrounding available data obtained from other projects. In other cases, assumptions can be made to overcome this issue. This paper proposes to attribute costs among project components through an allocation key based on Roe *et al.* (2021).

Roe *et al.* (2021) builds the most comprehensive database on the cost-effectiveness of land-based mitigation measures. The paper collects and harmonizes data from 10 different studies and 25 datasets, based on both economic and biophysical modelling.⁶ Mitigation potentials are estimated at the country level, according to the technical and cost-effective limitations of each mitigation measure. The resulting database covers more than 200 countries across the world for 20 mitigation activities (that correspond to those we can extract from EX-ACT results) and includes information on cost-effective feasibility of the individual mitigation activities. These can be successfully used to derive the relative costs of the mitigation measures, which can constitute an allocation key to split aggregated investments costs for projects where the detailed information is missing (Annex 1 provides details on how the allocation key was derived). The advantage of such approach is that it provides a global allocation key for all projects in the database for which detailed costs are missing. This, in turn, reduces the time dedicated to distributing the aggregate costs and limits the number of sources of bias as only one study is used to derive the allocation key.

Further, as the mitigation potential dataset is populated with more and more activities, the role of the allocation key becomes redundant as the higher number of data points allows for an improved statistical reliability of average costs.

Finally, among the objectives of conducting this work is to demonstrate how important it is to carefully document the investments, including the detailed costs, for deriving cost-effectiveness indicators and drawing valuable lessons learnt for future investments. Meeting this objective will allow eliminating the necessity of using allocation key in the future.

Step 5: Calculate the abatement cost and draw the marginal abatement cost curves

The abatement cost is calculated as the ratio between the overall investment in each mitigation measure (or group thereof) and the amount of GHG emissions or emission reductions during the investment period:

$$\text{Abatement cost} = \text{Investment} / \text{Amount of emissions during investment period}$$

To ensure the comparability of the investment costs of individual projects and allow for aggregation, the face values of investments have been converted into 2015 constant USD using World Development Indicators data and methods (World Bank, 2021).

⁶ The main limitation of such an approach is the use of costs that do not derive from direct reporting or study, but rather from biophysical or economic modelling. This partially removes the benefit linked to the use of real project costs for the construction of MACCs; however, it allows for the use of a consistent methodology and significantly reduced the need for additional research and resources.

In line with IPCC (2006) methodology and as reflected in EX-ACT, the investment period is understood as the time of project implementation, as indicated in project documentation, plus the capitalization period, that is, the time required for GHG fluxes to stabilize after the end of project activities.

Once the abatement costs are known, the MACC can be drawn by selecting the average or median values among those available in the database developed. While averages could represent the most appropriate choice in case of value distributions that assimilate a normal distribution, the presence of outliers may lead towards the choice of medians as the best representative values of the overall distribution.

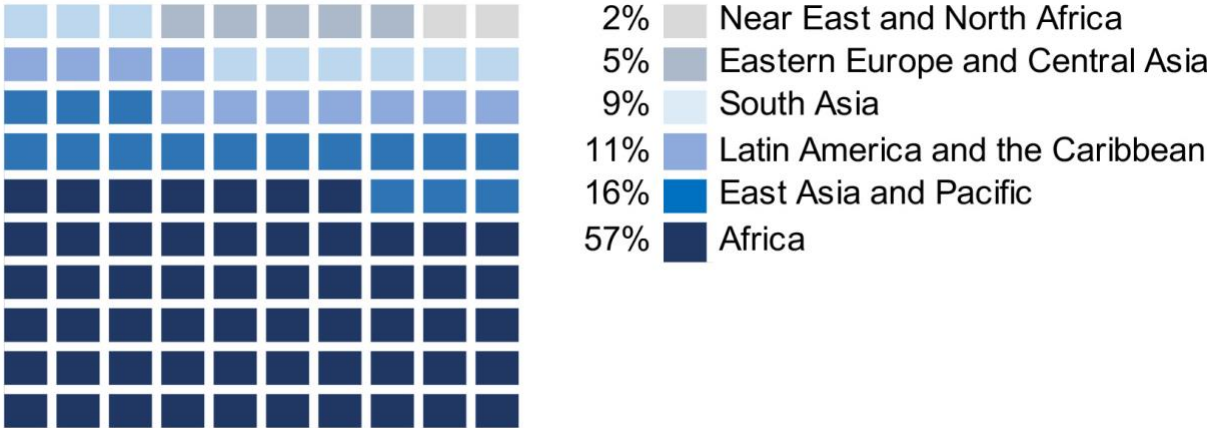
4 Application of the marginal abatement cost curves methodology to a case study of selected projects

The case study applies the proposed methodology to demonstrate its usefulness in providing recommendations for public agricultural investments. It builds on a portfolio of projects developed and implemented under the World Bank’s GAFSP.

The portfolio consists of 44 projects, either concluded or in the implementation stage. The projects were located in six regions (Figure 3): Africa (twenty-five projects – 57 percent); East Asia and Pacific (seven projects – 16 percent); South Asia (four projects – 9 percent); Eastern Europe and Central Asia (two projects – 5 percent); the Near East and North Africa (one project – 2 percent); and Latin America and the Caribbean (five projects – 11 percent). Projects covered a wide range of activities (Figure 4): avoidance of deforestation, afforestation, other land use change (e.g. from set-aside to cropland or annual to perennial cropland), annual croplands, perennial croplands, grasslands, livestock, forest management, inputs (such as fertilizers and pesticides) and investments (such as on-farm buildings or irrigation), and fisheries and aquaculture.

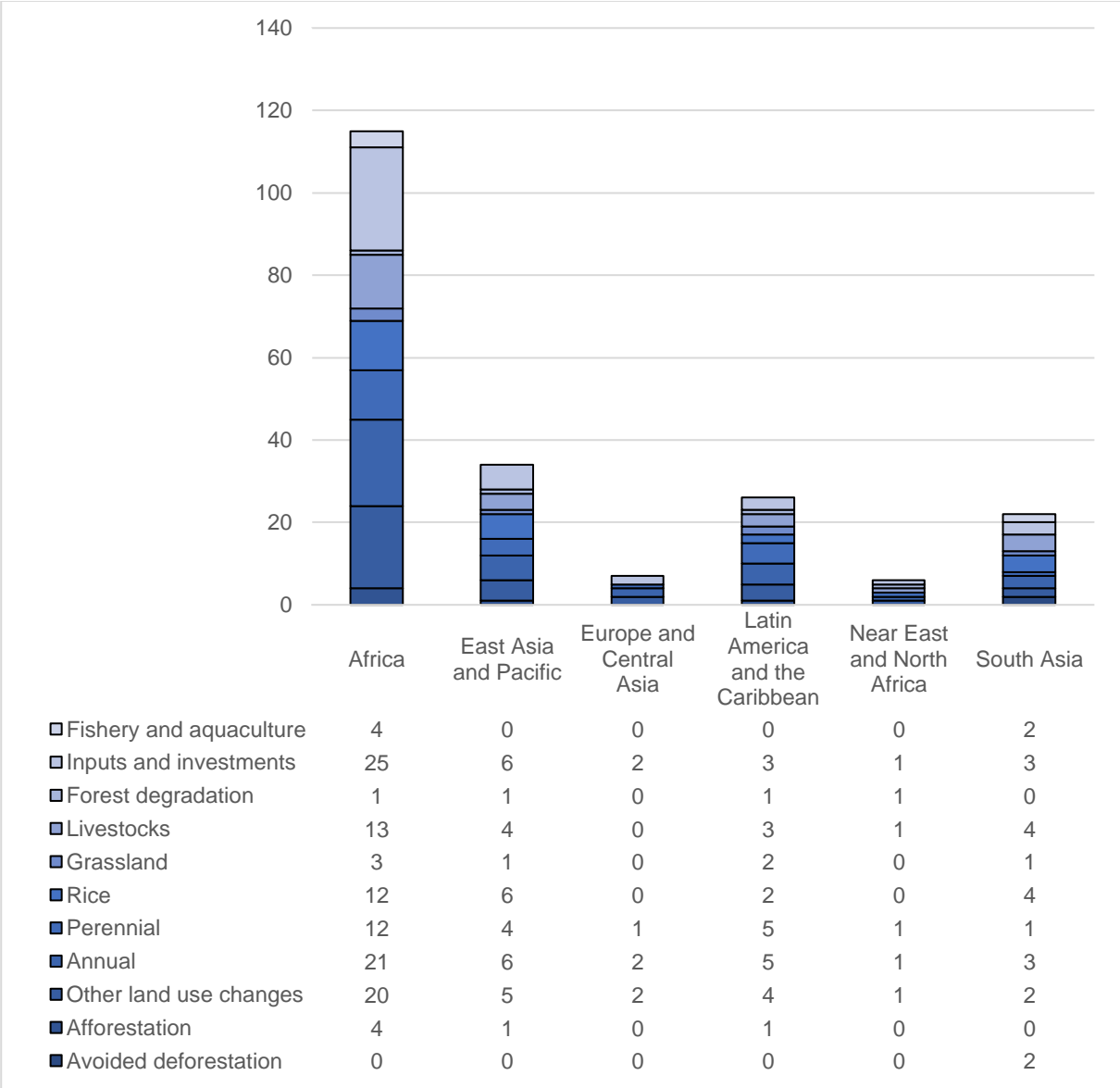
All GHG project appraisals were conducted between September 2020 and January 2021 by FAO climate change mitigation experts in a context of a portfolio review (GAFSP, 2021) using version 8 of the EX-ACT tool, based on the 2006 IPCC Guidelines for National Greenhouse Gas inventories (IPCC, 2006), their 2013 wetlands supplement (IPCC, 2014) and the IPCC Fourth Assessment Report (IPCC, 2007).

Figure 3. Sample overview: geographical distribution



Source: Authors’ own elaboration.

Figure 4. Sample overview: activity distribution



Source: Authors' own elaboration.

Due to large heterogeneity among projects, the portfolio represents an excellent base for a first application of the methodology for MACCs calculations. The wide range of agricultural activities and the large geographical coverage, in an otherwise limited sample size, provide insights into how the results may differ across activities and climatic conditions. Further, the time concentration for the appraisals and the fact that all projects fall under the same funding mechanism ensure consistency across the project assessments and their investments.

4.1 Estimating mitigation potential of measures analysed in the portfolio (step 1, step 2 and step 3 of the methodology)

Throughout the portfolio analysis of the sample, EX-ACT analysts examined GAFSP project documents (including the Economic and Financial Analysis) and retrieved information on activities generating changes in GHG emissions.

The retrieved activities included:

- land uses and livestock categories;
- input, fish, energy and infrastructure;
- number of units affected by the specific activity (e.g. hectares of land, heads of livestock, tonnes of fish catch, tonnes of inputs, etc.);
- details of management practices (e.g. soil management for cropland, feeding practices on livestock, types of fish gear for fisheries, etc.).

Once the information was identified, the EX-ACT experts conducted an EX-ACT analysis. The carbon balance for each project activity was estimated by comparing two scenarios: a “with project” scenario and a reference scenario calculating the mitigation or emission potential of project activities *vis-à-vis* an alternative scenario in which the project is not implemented. Project teams have subsequently crosschecked and validated the EX-ACT analysis of each project.

Overall, the GAFSP portfolio of 44 projects was a net reducer of GHG emissions, with an overall carbon-balance of -7.58 million tCO₂-eq. Approximately 90 percent of all net GHG emission removals and carbon sequestration of GAFSP-financed projects could be attributed to the following three activities:

- The improved management and restoration of annual croplands by means of climate smart agriculture (CSA) practices (including improved agronomic practices, nutrient management, no tillage and residue retention, water management and/or manure application).
- The development and improved management of agroforestry and perennial cropland systems.
- Afforestation activities on land previously subject to other land uses.

More information on the projects analysed and the general task developed through the GAFSP Grant can be found in GAFSP (2021).

To facilitate construction of MACCs, the activities of each project have been assigned to 16 homogenous activity categories combining measures with layers 1 to 3 presented in Table 1. As a result, each category includes activities with a clear linkage to the most pertinent EX-ACT submodule. Activities can entail direct land or livestock management actions, as well as capacity building that is specifically targeted at land or livestock management (Table 2).

Table 2. Mitigation measures identified in the Global Agriculture and Food Security Program project portfolio

EX-ACT module(s)	Most pertinent EX-ACT submodule	Activity category considered for final list of measures for the portfolio	Activity example
Land use change	Deforestation	Avoided deforestation	Fencing and protection service for forested land
Land use change	Afforestation	Afforestation	Direct plantation activities; nursery establishment
Land use change	Other land use changes	Conversion of land use	Establishment of new crops on unused land
Cropland	Annual cropland	Manure application on annuals	Manure application on annuals
Cropland	Annual cropland	Improved soil management on annuals	Reduction in the use of tillage, improvement in nutrient management
Land use change + cropland	Flooded rice	Land use change to flooded rice	Introduction of flooded rice crops on previously rainfed annual cropland
Cropland	Flooded rice	improved management and practices for flooded rice	Change in the water regime during or prior to the cultivation, change in cropping days
Forest management	Forest management	Reducing forest degradation	Fire and disturbance avoidance, fuelwood collection management
Grassland and livestock	Grassland	Improving grassland degradation state	Livestock grazing management, sustainable land management practices
Cropland	Perennial cropland	Improvements in perennials/agroforestry systems	Change in agroforestry type to enhance productivity
Cropland + inputs	Annual cropland	Improved water management on annuals	Improved water management on annuals
Cropland	Perennial cropland	Land use change to perennials/agroforestry	Introduction of new agroforestry or tree crops
Land use change + cropland	Annual cropland	Land use change to annual cropland	Introduction of new annual and pluriannual crops
Land use change + grassland and livestock	Grassland	Land use change to grassland	Establishment of a new rangeland, planting of new grass species
Grassland and livestock	Livestock	Improved livestock practices	Improved feeding or breeding practices
Coastal wetlands and fisheries	Fisheries	Improvements in fisheries and aquaculture management	Improvement in fuel, introduction of new productive species

Source: Authors' own elaboration.

4.2 Retrieving and calculating the abatement cost and drawing marginal abatement cost curves (step 4 and step 5 of the methodology)

Once the project appraisals were completed, all information related to the costs of implementing individual activities was isolated to build the MACCs for the portfolio.

EAs, project documents and cost reporting tables were consulted to associate activities with their respective costs. 10 projects allowed for the collection of real costs from the respective documentation. A total of 27 observations was collected for these projects. 9 other projects did not allow to retrieve precise enough data to associate implementing costs and mitigation measures. For these 9 projects, it was possible to obtain 34 additional cost observations by distributing aggregated project costs according to the allocation key derived from Roe *et al.* (2021) (as described in step 3 of the methodology). Table 3 summarizes the results of the cost allocation process.

Table 3. Mitigation measures identified in the Global Agriculture and Food Security Program project portfolio

Practice	Real cost observations	Weighted cost observations
Avoided deforestation	0	0
Afforestation	1	2
Conversion of land use	0	0
Manure application on annuals	2	6
Improved soil management on annuals	5	7
Land use change to flooded rice	0	1
improved management and practices for flooded rice	3	5
Reducing forest degradation	0	2
Improving grassland degradation state	0	3
Improvements in perennials/agroforestry systems	3	5
Improved water management on annuals	5	9
Land use change to perennials/agroforestry	5	10
Land use change to annual cropland	0	3
Land use change to grassland	1	3
Improved livestock practices	2	5
Improvements in fisheries and aquaculture management	0	0
Total	27	61

Source: Authors' own elaboration.

Next, all costs have been normalized according to constant 2015 USD to allow the comparison of cost-effectiveness across projects with different starting years and implementation time.⁷ In case of project costs reported in different currencies from USD, exchange rates reported in the project documents have been used whenever available, and historical exchange rates as available in the World Bank Databank (World Bank, 2021) have been applied when necessary.

⁷ Starting years and implementation periods of the projects have been reported according to official project documents.

The final list of mitigation measures and associated costs included 61 observations from a tailored subset of projects (19), representing a consistent and reliable framework to build upon for a first MACCs analysis. Coherently with the results of the wider portfolio assessment, most of the activities covered land use to agroforestry (10) and irrigation (9). The final sample did not cover all activities analysed in the context of the portfolio assessment. Avoided deforestation, other land use changes and aquaculture and fishery management did not return neither real nor weighted cost observations and have thus been excluded from further analysis.⁸

Table 4. Mitigation measures isolated in the portfolio (tCO₂-eq)

Mitigation potential	Min	Max	Average	Standard deviation
Afforestation	3 534.0	1 539 863.0	771 698.5	768 164.5
Annual cropland – manure application	1 564.0	1 423 158.0	311 471.6	504 486.2
Annual cropland – improved soil management	6 797.0	267 997.0	96 081.6	90 756.5
Land use change to flooded rice	43 107.0	43 107.0	43 107.0	0.0
Flooded rice – improved practices	34 693.0	1210 806.0	397 608.8	423 060.5
Forest management – reducing degradation	6 884.0	1 087 548.0	547 216.0	540 332.0
Grassland – improved degradation state	587.0	767 191.0	293 977.3	337 809.4
Improvements in agroforestry systems	16 668.0	975 910.5	262 258.5	362 665.1
Improved water management	7 091.8	1 168 374.0	301 919.3	393 190.5
Land use change to agroforestry	18 451.1	1 083 792.4	347 276.1	340 786.3
Land use change to annual cropland	9 644.0	887 489.9	328 963.3	396 289.9
Land use change to grassland	495.0	313 402.0	183 056.0	132 972.4
Livestock – improved practices	609.0	13 665.0	5 016.2	4 492.4

Source: Authors' own elaboration.

Table 4 summarizes the final list of isolated activities and provides key descriptive statistics on their mitigation potential across projects; forest-based activities display the highest absolute mitigation potential of all the measures considered, while land use change to flooded rice and livestock management activities are the measures with the lowest mitigation potential.

Table 5 provides descriptive statistics of costs for the considered activities. Land use change to flooded rice measures and livestock improved practices result the most expensive of all mitigation activities. Afforestation and forest management are instead the least costly.

⁸ All mitigation measures have positive implementation costs in the context of project budgets. This also includes prevention activities, such as avoidance of deforestation, fire or degradation. The lack of cost observation is thus solely to associate with data availability limitations.

Table 5. Abatement costs isolated in the portfolio

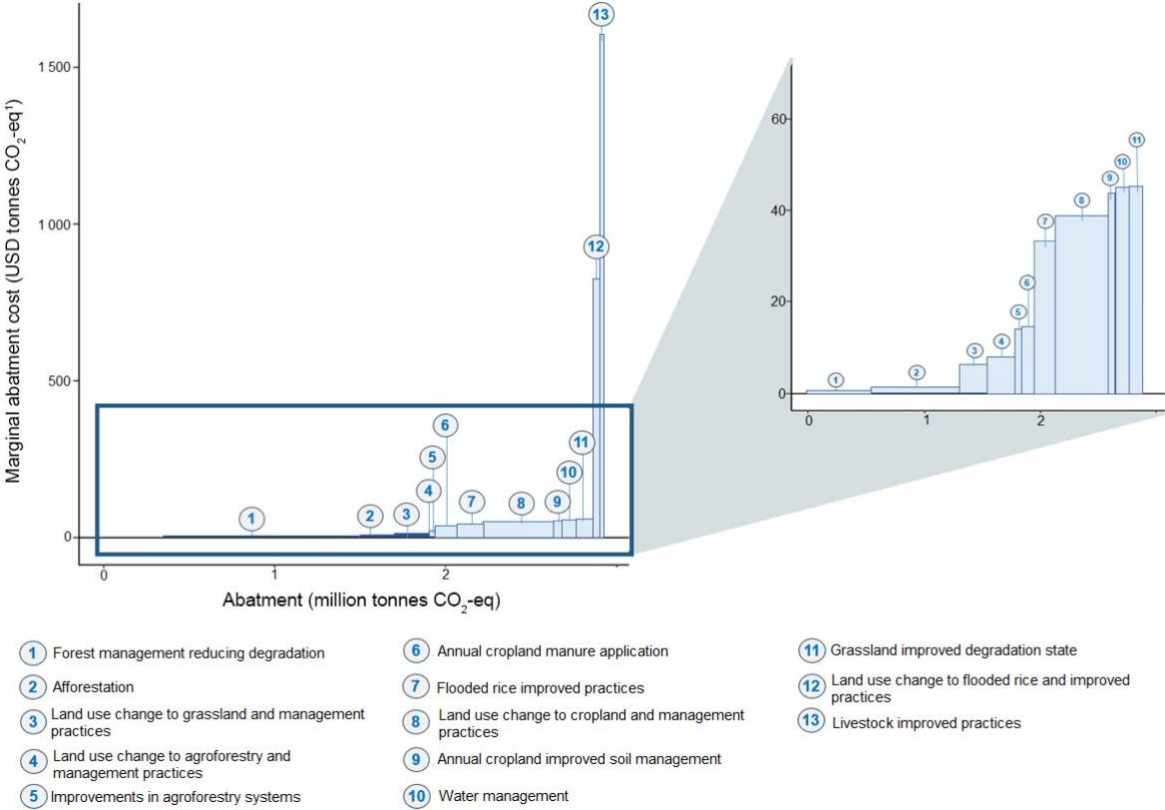
Abatement cost	Min	Max	Average	Standard deviation
Afforestation	0.4	1.7	1.1	0.6
Annual cropland – manure application	0.5	386.2	75.7	139.4
Annual cropland – improved soil management	4.7	205.3	78.6	79.0
Land use change to flooded rice	817.1	817.1	817.1	0.0
Flooded rice – improved practices	23.1	214.1	68.4	73.3
Forest management – reducing degradation	0.0	0.6	0.3	0.3
Grassland – improved degradation state	7.7	82.3	45.0	30.5
Improvements in agroforestry systems	10.0	80.3	29.8	26.8
Improved water management	2.9	260.2	86.9	94.7
Land use change to agroforestry	1.9	569.0	63.6	168.5
Land use change to annual cropland	16.9	60.7	36.6	18.2
Land use change to grassland	2.4	31.3	13.2	12.9
Livestock – improved practices	0.0	12720.3	3561.9	4755.8

Source: Authors' own elaboration.

Given the small sample size, and to reduce influence of the outliers, the portfolio’s MACC has been calculated and drawn considering on the vertical axis, the median cost of mitigation expressed in constant 2015 USD, and on the horizontal axis the median mitigation of the measures considered.⁹

Results show that, at a globally aggregated level, about 2 926 521 tonnes of CO₂-eq could be captured for a total value of USD 1 932 million, or an average of USD 215 per tonne CO₂eq (Figure 5). The abatement potential of most agricultural mitigation activities considered is in line with the climate needs for 2030 and beyond: mitigation activities that can be implemented at a lower cost than USD 100/tCO₂-eq are in the middle and low range for carbon prices in 2030 and 2050 that are compatible with a 1.5 °C pathway (Rogelj *et al.*, 2018). All activities considered, except flooded rice management after land use changes and livestock management, fall into the range.

Figure 5. The marginal abatement cost curves for the Global Agriculture and Food Security Program portfolio



Source: Authors’ own elaboration.

The compatibility of climate-smart agricultural practices with the 1.5 °C threshold gains significance, particularly in the context of achieving food security and Sustainable Development Goal 2 (SDG 2). Almost all analysed activities demonstrate the potential to enhance food

⁹ The geographical distribution of the sample, albeit quite varied in terms of states represented, displayed homogeneity in types of climates considered. More than 91 percent of the observations (56) reflect activities in tropical climates, with the remaining eight percent (6) being in temperate areas. As a result, the numbers were used in aggregated form in MACCs calculations.

production and security while mitigating climate change at a relatively low cost. Even those activities surpassing the USD 100 threshold would still contribute to food systems functioning as net carbon sinks, thus addressing the joint agenda on food security and nutrition, while ensuring alignment with global climate imperatives (FAO, 2023).

Forest degradation management and afforestation are the least expensive measures to implement to maximize mitigation. Other significant sources of mitigation at a low cost are grassland and perennial crops improvement following a land conversion. The least cost-efficient activities analysed in the portfolio appear to be livestock improvements and land use change to flooded rice, which have costs around 1 000 times higher than all other measures in the portfolio.

Restoration of forests and afforestation, the most viable options for climate action in the portfolio, are mitigating about 600 000 and 800 000 tonnes of CO₂-eq at a median cost of USD 0.3 and USD 1 per tonne, respectively. Forests are important carbon sinks and these results confirm other findings in literature on the relative cost-efficiency of activities in forested areas (Moran *et al.*, 2008; Climate Works Australia, 2010; Gillingham and Stock, 2018). For example, Gillingham and Stock (2018) estimate that the cost of afforestation is likely to fall between USD 1 and 10 per tonne of CO₂-eq.

Grassland management practices and agroforestry improvements after land use changes are also beneficial options, having a relatively low abatement cost. Sustainable management practices (climate smart agriculture) enhance mitigation benefits by increasing soil organic carbon and biomass carbon storage in grasslands and agroforestry systems. More specifically, grassland management practices are linked to restoration activities: in most projects land converted to grassland was abandoned or degraded and soil organic carbon benefits accruing from a sustainable recovery of the land represented an efficient way of mitigating climate change. Similarly, agroforestry systems were mostly implemented on abandoned lands. The significant mitigation potential of these activities mostly originates from the substantial contribution of woody biomass to carbon sequestration. As a result, by producing biomass and capturing carbon, these systems are often among recommend climate smart practices (Shibu and Sougata, 2012).

At the other end of the curve, livestock activities are associated with the highest costs per abatement potential. Interventions on livestock in the context of the GAFSP activities usually focused on productivity improvements as directly correlated with an increase in the number of heads, a source of emissions. Practices with significant climate co-benefits, such as feeding and breeding improvements, were rarer, and often still associated with increasing livestock numbers, making the aggregated mitigation potential limited compared to the investment costs. Flooded rice management practices after land use changes also show significant costs per abatement unit, but the evaluation is dependent on a single observation and no conclusions should be drawn from the data.

Management practices on existing annual cropland are also at the high end of the MACC. For improved water management, this is due to the significant costs associated with the implementation of the necessary infrastructure; for soil management, this may be linked to the emissions associated with residue retention practices, partially offsetting the increases in carbon storage linked to the activity itself and to the application of no till practices. The curve estimates a cost of USD 43.5 per tonne of CO₂-eq reflecting what found by Gillingham and Stock (2018), who propose a value close to USD 57 per tonne of CO₂-eq.

5 Limitations

The proposed methodology applies some assumptions and simplifications to render it operational and to deliver results that are comparable across countries and financing entities. These assumptions and simplifications bear some consequences, which are briefly discussed below.

5.1 General limitations

By construction, bottom-up MACCs face two major limitations. First, time is assumed as exogenous, and therefore costs are static and intertemporal interactions ignored. Second, embracing a bottom-up perspective, these analyses focus on in-depth sector details rather than aggregate or total estimates. Therefore, due to the attention paid to microeconomic characteristics, macroeconomic dynamics are not fully captured. As a result, aspects like growth and changes in supply and demand are oversimplified. However, while on the one hand it is undeniable that the main weakness of bottom-up approaches lies in providing an oversimplified representation of complex realities; on the other hand, it can also be argued that their main strength is the simplicity of the results.

5.2 Limitations related to estimation of costs of abatement options

The MACCs provided through this research are solely focused on public costs of each measure that is the amount of investment required per tCO₂-eq abated. As such, implicit costs of adoption and other hidden costs not included in project budgets, as well as additional costs that could not be directly linked to specific measures implemented, have been excluded from the analysis. This also includes recurrent costs that beneficiaries may incur into after project implementation has ended: GHG appraisals assume that after the implementation practices introduced will be maintained unless they are fully dependent on external funding (e.g. direct fertilizer provision). After project closure, the costs linked to such practices are not budgeted anymore, and as such not included. Benefits of the implementation of each measure that are not linked to climate mitigation are also disregarded. This is a direct consequence of the choice of the primary target group of this research that is international funding entities interested in understanding the direct mitigation potential of their investments in the AFOLU sector.

5.3 Limitations related to net present value (NPV)

Ideally, the investment in a group of mitigation measures should be calculated using the NPV of cash flows related to the investment. Yet, identifying an adequate discount ratio for each project proves challenging. For projects with quality EFAs discount ratios are available; however, their selection is dependent on the author providing the analysis. As each project looks for the best value for its individual financial assessments applying discount rates to investment costs according to their EFAs may not be optimal for cross-project analysis. Further, for many projects the discount ratios are not available at all. One solution to this challenge could be to identify a methodology for selecting best discount ratios for each individual project. Many existing MACCs simply apply the central bank's discount rates or other private or social discount rates (Shishlov and Bellassen, 2014; Ekins, Kesicki and Smith, 2011; Moran *et al.*, 2011), however, this could prove difficult given the large country and time coverage of the underlying database. Further, using countries central banks' discount rates is likely not to help in comparability of results if projects originating from different countries are

aggregated together. As a result, while including NPV would have allowed for a more holistic cost-benefit analysis of the measures analysed, it also subjected the research to further uncertainty and assumptions and thus been avoided.

5.4 Limitations related to EX-Ante Carbon-balance Tool (EX-ACT) assessments

GHG appraisals are subject to a set of assumptions in case the available information about analysed projects is limited. These assumptions, although streamlined through the concerted approach, are context and project specific and, as such, subject to uncertainty. Given this limitation, the approach proposed in this paper – focusing on general measures identified, rather than specific mitigation initiatives with higher granularity – allows for a partial reduction of uncertainties in the overall assessment. On the other hand, it also generates an additional constraint in representativeness of the measure appraised: management activities on annual cropland may generate carbon balances that are significantly different from one another. Future research will be aimed at allowing more granularity in the examination of cost-effectiveness of AFOLU measures.

Further, EX-ACT assessments were performed at different stages of implementation. In order to minimize uncertainty on the association between costs actually incurred in and mitigation really achieved, it would be essential to prefer *ex post* GHG assessments and their relative cost tables. The use of *ex ante* assessments is subject to potential overestimation of GHG fluxes as well as to potential misestimation of costs as they draw from projections and assumptions about project implementation.

5.5 Limitations related to interactions between abatement measures

Interactions between mitigation measures are not taken into account, yet, Vermont and de Cara (2010) note that an interesting feature of constructing MACCs in the agricultural sector lies in the interactions between different mitigation activities. For example, carbon emissions associated with different kinds of agricultural soils may be affected by the number of livestock heads on a given patch of land, which in turn may affect the number of fertilizers used, which in turn may affect carbon soil emissions, and so on. While EX-ACT allows computing mitigation interactions within the specific annual cropland section, the tool does not consider interactions between activities afferent to distinct submodules or modules. This, on one hand, ensures that the carbon balance obtained from every intervention is specific to that and only that activity, thus representing an added value of the methodology developed; on the other hand, it also implies that other environmental externalities that may affect the overall carbon balance of the project under scrutiny are not taken into account. It is relevant to register this because mitigation benefits of a specific activity may consequently be lower or higher than those captured through the EX-ACT appraisal. The issue is often noted in MACCs built on the engineering approach, in which the abatement potential of each measure is defined separately.

5.6 Limitations related to non-capture of other environmental externalities

MACCs constitute an extremely useful indication on how to steer decision making towards the most efficient climate mitigation activities, yet it should not be taken as an exhaustive environmental or socioeconomic assessment of the impacts of such activities (FAO, 2012).

There may be cases of unviable measures, which in MACCs analysis alone would result beneficial. This is the case when other environmental externalities (e.g. biodiversity, climate adaptation) have a strong negative correlation to the positive mitigation impacts or when socioeconomic effects, such as increase in food insecurity or worsening of social conflict, render the activities unviable in the targeted context. To adequately respond to the challenges posed by the climate crisis it is thus fundamental to incorporate other considerations in judging the quality of the planned mitigation measures.

5.7 Limitations related to heterogeneity and external validity

One of the main challenges in estimating MACCs for agriculture lies in the pronounced heterogeneity of both cost and biophysical conditions across different activities, as highlighted by substantial standard deviations in Table 5. This issue underscores the complexity and specificity of agricultural mitigation actions, where factors such as soil characteristics, climate variations, socioeconomic contexts, institutional frameworks and other site-specific conditions significantly influence both costs and mitigation potentials.

Given the context-specific nature of agricultural mitigation activities, it becomes evident that a one-size-fits-all approach, as implied by global-level MACCs, may not capture the nuanced intricacies of diverse agroecological settings. A more robust and informative strategy would involve disaggregating MACCs based on climate zones, as these zones encapsulate specific soil and biomass conditions that directly impact GHG calculations. This approach, by aligning with IPCC climate zones, could offer more internally consistent mitigation potentials at tier 1 level, potentially presenting a higher degree of homogeneity in cost observations. The work initiated within this paper aims at expanding the underlying database to provide sufficiently granular results for addressing these limitations.

6 Conclusions

This paper proposes a methodology for calculating MACCs for public finance in agriculture using granular data on specific activities from investment projects. The developed MACCs target public investment decision makers from the international and national financing institutions, as well as governments. The methodology is based on information obtained from agricultural projects implemented by IFIs and carbon accounting appraisals conducted using the FAO EX-ACT. The curves are estimated through a bottom-up approach, in which actual data on mitigation potential of agricultural investments and their associated costs are used to derive the cost-effectiveness of individual agricultural activities.

As the methodology draws on actual data from investments in agriculture, it offers a unique opportunity to calculate the bottom-up MACCs from public investments in the agricultural sector to inform future investments. The results that the application of the methodology provides can be tailored to specific circumstances, particularly in terms of geographical and climatic representation, as the methodology disaggregates the results by location, climate, moisture and soil type. In this way, it offers a strong base to build tailored recommendations and steer policy and investment towards sustainable development.

When estimating the mitigation contribution of AFOLU projects the size of the investments, the type of implemented activities as well as the specific geographical conditions prevailing in the projects' areas (notably, climate, moisture and soil type) have a significant effect on the results, i.e. the carbon balance. In order to determine the most climate-mitigation friendly investment options, it is crucial to link activity-specific costs and contextual mitigation potentials - that is, to derive marginal abatement cost curves.

The case study complements the MACCs methodology with a practical example. It collects data from 44 projects financed through the GASFP Grant of the World Bank and builds MACCs based on the GHG assessments conducted by the FAO, EX-ACT Unit, over September 2020–January 2021.

The MACC estimated in this case study represents a limited but precious reference for agricultural investments funded by IFIs. Even taking into consideration the limited sample feeding into results reported in the paper, the MACC provides a first indicative association between mitigation measures and their implementation costs. The case study shows the recommendations that the ranking of measures makes possible to formulate. By listing options from the least to the most expensive, the MACC orders information by key areas of investments, offering critical insight on which investments can deliver the highest benefits at the lowest costs.

Results appear to be consistent with relevant literature on the subject (Moran *et al.*, 2008; Climate Works Australia, 2010; Shibu and Sougata, 2012; Gillingham and Stock, 2018), which strengthens the legitimacy of this methodology towards providing key evidence on most cost-effective climate change mitigation solutions in agriculture. The case-study confirmed the crucial role that forestry related practices, namely improved management and afforestation, can play in meeting the 1.5–2 °C warming targets. According to IPCC (2019), reaching these targets is conditional to investing in such strategies. One-quarter to one-third of the abatement required could be met through forest related activities (Austin *et al.*, 2020). This is a key outcome. Afforestation activities may be perceived as costly in absolute terms. Planting new trees is likely to come at a quite higher cost than improving soil management in annual

cropland. However, when the costs are compared in relative terms, that is, in terms of their mitigation potential (the abatement cost), then afforestation results appear to be by far more cost-efficient.

Future iterations in the application of the methodology could expand on several relevant aspects to build on the present case study and ensure a higher representativeness of results. Mainly, populating the sample size with more projects and activities would increase the reliability of results. This would allow to better weight outliers and disaggregating measures by climate and geographical contexts – agriculture activities are highly context specific, and the cost-efficient ranking is likely to change accordingly. Further, this would offer the chance of reaching a higher level of granularity in the agriculture measure specification, for instance by allowing to differentiate between types of agroforestry systems. Having more data points would also ensure more robust results.

Finally, systematic inclusion of detailed data on expenditures associated with individual project activities in project documents would allow to include more project in this type of analysis and avoid using allocation keys that at present are often required to construct MACCs. It is paramount to improve the quality of cost data and to harmonize project documents with comparable cost tables. The methodology proposed in this paper and the case study demonstrate that there are large benefits in doing that – having detailed understanding of cost-effectiveness of mitigation measures in agriculture for future investments is a key asset in meeting the climate change mitigation commitments, such as those expressed under the Paris Agreement.

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Annexes

Annex 1. Allocation of costs

The methodology included in this paper includes an allocation key based on a paper by Roe *et al.* (2021), which develops an assessment of global mitigation potentials of land-based measures. The paper collects research on land-based mitigation potentials at the country, region and global levels, based on both economic and biophysical modelling.

Mitigation potentials are estimated according to the technical and cost-effective limitations of each mitigation measure. The first aspect reflects available technology and geophysical aspects of countries, while the second introduces an economic boundary for the estimate of the mitigation potentials, equivalent to USD 100/tCO₂-eq abated for each measure. The boundary is “in the middle of the range for carbon prices in 2030 for a 1.5 °C pathway, and at the low end of the range in 2050” (Roe *et al.*, 2021, p.3). More information can be found in the paper and its supporting materials. The link to the Roe database is provided in the references section.

The land-based measures are categorized in a similar fashion to the groupings proposed in step 3 of the current methodology. Table A1 summaries the mapping between the measures, as reported in each different methodology.

Table A1. Linking EX-Ante Carbon-balance Tool (EX-ACT) groupings

Measure as reported in Roe <i>et al.</i> (2021)	Corresponding EX-ACT grouping	Additional comments
Deforestation (global) Deforestation (tropics)	Avoided deforestation	The granularity of modelled data allows for a distinction between tropical climates and all other climates
Afforestation (global) Afforestation (tropics)	Afforestation/reforestation	The granularity of modelled data allows for a distinction between tropical climates and all other climates
N/A	Other land-use change improvements	Roe <i>et al.</i> (2021) does not include a specific measure covering this grouping
Soil organic carbon in cropland Crop nutrient management	Improvement of annual crops	The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure
Soil organic carbon in cropland Crop nutrient management	Improvement of annual crops converted from other land uses	The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure
Soil organic carbon in cropland Crop nutrient management Agroforestry	Improvement of perennial/tree crops	The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure

Measure as reported in Roe <i>et al.</i> (2021)	Corresponding EX-ACT grouping		Additional comments
Soil organic carbon in cropland Crop nutrient management Agroforestry	Improvement of perennial/tree crops converted from other land uses		The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure
Rice management	Improvement of flooded rice fields		
Rice management	Improvement of flooded rice fields converted from other land uses		
Soil organic carbon in grasslands Grassland and savannah fire management	Improvement of grasslands		The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure
Soil organic carbon in grasslands Grassland and savannah fire management	Improvement of grassland converted from other land uses		The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure
	Enteric fermentation Manure management	Improvement of livestock	The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure
	Forest management (global) Forest management (tropics)	Forest degradation management	The granularity of modelled data allows for a distinction between tropical climates and all other climates
	N/A	Improvement of fishing and aquaculture	Roe <i>et al.</i> (2021) does not include a specific measure covering this grouping.
	Reduce peatland degradation (avoided degradation) Peatland restoration	Inland wetland management	The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure.
	Mangrove restoration and management Reduce peatland degradation (avoided degradation) Peatland restoration	Coastal wetland restoration	The allocation key for this EX-ACT grouping is chosen in accordance with information on the specific measure.

Source: Authors' own elaboration based on Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A. *et al.* 2021. Land-based measures to mitigate climate change: Potential and feasibility by country. *Global Change Biology*, 27: 6025–6058. <https://doi.org/10.1111/gcb.15873>

Mitigation potentials are always associated to activity units, that is, the number of hectares, heads or tonnes of catch impacted by each activity depending on the technical or cost-effective boundary. Given that the aim of the paper is to develop MACCs relative to each mitigation activity, the relationships between cost-effective activity units are used as proxy of the relative cost of each mitigation measure.

Table A2 indicates how Roe *et al.* (2021) derive cost-effective value by activity to provide more clarity to potential users of the methodology contained in this paper.

Table A2. Methods for deriving cost-effective mitigation potential

Mitigation category	Mitigation measure	Definition	Method
Forests and other ecosystems – protect	Reduce deforestation	Avoided emissions from deforestation. Forests are defined as 30% or greater tree cover.	Cost-effective potential was calculated as the difference between business as usual (BAU) and USD 100/tCO ₂ -eq. Carbon price values are in constant 2014 USD.
		Avoided emissions from deforestation (forests as defined in (FAO, 2020b).	cost-effective potential was calculated at a carbon price below USD 100/tCO ₂ -eq compared to baseline levels. Carbon price values are in constant 2017 USD.
	Reduce mangrove loss	Avoided emissions from degradation and/or anthropogenic loss of carbon stocks in mangrove ecosystems.	Cost-effective potential (<USD 100/tCO ₂ -eq) was estimated as 90% adoption of technical potential, following Griscom <i>et al.</i> (2017).
	Reduce peatland degradation	Avoided GHG emissions (CO ₂ , CH ₄ and N ₂ O) from degradation of intact peatlands (does not include conversion of vegetation).	The economic mitigation potential of peatland protection was calculated as the difference between SSP2_RCP2p6+PeatProt (land-based climate policy incl. peatland protection) – SSP2_Ref (no climate policy) in the year 2035 (<USD 100/tCO ₂ -eq).
Forests and other ecosystems – manage	Improve forest management	Avoided emissions and enhanced sequestration from improved natural forest management, including reduced-impact logging, extended harvest rotations, increased post-harvest sequestration rates, and designation of set-aside areas for protection from logging activity.	Cost-effective potential (<USD 100/tCO ₂ -eq) was estimated as 60% of technical potential, following Griscom <i>et al.</i> (2017).
		Enhanced carbon sequestration from improved forest management activities.	Technical potential was calculated at a constant carbon price of USD 2 000/tCO ₂ -eq to stimulate the maximum available carbon in the model. Cost-effective potential was the carbon sequestration potential given for scenarios with a carbon price below

Mitigation category	Mitigation measure	Definition	Method
			USD 100/tCO ₂ -eq in 2050 compared to baseline levels. Carbon price values are in constant 2017 USD.
	Grassland fire management	Avoided emissions from grasslands fires.	Cost-effective potential (<USD 100/tCO ₂ -eq) was estimated as 30% adoption of technical potential, following Griscom <i>et al.</i> (2017).
	Afforestation and reforestation	Carbon sequestration by shifting from non-forest cover to forest cover at 30% tree cover threshold with a region-specific mix of plantation forestry and natural forest regrowth.	Cost-effective potential calculated as at USD 100/tCO ₂ -eq relative to BAU. Carbon price values are in constant 2014 USD.
		Carbon sequestration from afforestation and reforestation (forests as defined in FAO (2020b).	Technical potential was calculated at a constant carbon price of USD 2 000/tCO ₂ -eq to stimulate the maximum available carbon in the model. Cost-effective potential was the carbon sequestration potential given for scenarios with a carbon price below USD 100/tCO ₂ -eq in 2050 compared to baseline levels. Carbon price values are in constant 2017 USD.
	Mangrove restoration	Carbon sequestration from restoring mangroves lost since 1996, after excluding those converted to urban land or lost to erosion.	The proportion of cost-effective (<USD 100/tCO ₂ -eq) potential (30% adoption of technical potential) was estimated following Griscom <i>et al.</i> (2017).
	Peatland restoration	Avoided GHG emissions (CO ₂ , CH ₄ and N ₂ O) from restoration (re-wetting) of degraded peatlands.	The economic mitigation potential of peatland restoration was calculated as the difference between SSP2_RCP2p6+PeatRestor (land-based climate policy including peatland protection +restoration) and SSP2_RCP2p6+PeatProt (land-based climate policy including peatland protection) in the year 2035 (<USD 100/tCO ₂ -eq).
	Enteric fermentation	Avoided CH ₄ emissions from ruminant livestock enteric fermentation through improved feed conversion, antibiotics, bovine somatotropin (bST), propionate precursors, antimethanogens, and intensive grazing.	Cost-effective mitigation potential was calculated based on the quantity of mitigation available from options with break-even prices at or below USD 100/tCO ₂ -eq (using constant 2017 USD carbon price values).

Mitigation category	Mitigation measure	Definition	Method
	Manure management	Avoided CH ₄ and N ₂ O emissions from livestock manure management in anaerobic systems through incorporation of small-scale or large-scale anaerobic digesters.	Cost-effective mitigation potential was calculated based on the quantity of mitigation available from options with break-even prices at or below USD 100/tCO ₂ -eq (using constant 2017 USD carbon price values).
	Nutrient management	Avoided N ₂ O and CH ₄ and changes in carbon sequestration in cropland soils associated with nitrogen application through changes in fertilizer application and management practices: split fertilization, 100 percent crop residue incorporation, nitrification inhibitors, and reducing nitrogen fertilizer applications by 20%.	Cost-effective mitigation potential was calculated based on the quantity of mitigation available from options with break-even prices at or below USD 100/tCO ₂ -eq (using constant 2017 USD carbon price values).
		Avoided N ₂ O emissions (direct and indirect) and production-linked CO ₂ emissions from reducing total fertilizer application with best practices and/or improved technologies.	Cost-effective potential (<USD 100/tCO ₂ -eq) was estimated as 90% of technical potential, based on Griscom <i>et al.</i> (2017).
	Rice cultivation	Avoided CH ₄ and N ₂ O emissions and enhanced soil organic carbon sequestration from rice cultivation through: nutrient management (reduced or optimized nitrogen fertilizer application, use of slow release fertilizer, application of nitrification inhibitors, switching from urea to ammonium sulphate), residue management (100% incorporation), water management (midseason drainage, alternate wetting and drying, switching from irrigated to dryland rice), dry seeding, tillage strategies, and combinations of these activities.	Cost-effective mitigation potential calculated based on the quantity of mitigation available from options with break-even prices at or below USD 100/tCO ₂ -eq (using constant 2017 USD carbon price values).
		Avoided CH ₄ and N ₂ O emissions associated with anaerobic decomposition by employing the periodic draining of rice soils and the removal of rice residues in flooded and upland rice production lands.	Cost-effective mitigation (<USD 100/tCO ₂ -eq) was estimated as 60% adoption of technical potential, following Griscom <i>et al.</i> (2017).
Agriculture – sequester carbon	Agroforestry	Carbon sequestration from adding aboveground woody carbon storage in agriculture systems	We estimated the technical sequestration potential using a 50% adoption scenario and cost-effective sequestration potential

Mitigation category	Mitigation measure	Definition	Method
		(crop and pasture pixels with <25% tree cover).	using a 10% adoption scenario which is a proxy for mitigation at USD 100/tCO ₂ -eq (based on Griscom <i>et al.</i> [2017]).
	Biochar from crop residues	Enhanced carbon sequestration by amending agricultural soils with biochar, which increases the agricultural soil carbon pool by converting rapid-mineralizing carbon (crop residue biomass) to persistent carbon (charcoal) through pyrolysis.	The cost-effective potential (<USD 100/tCO ₂ -eq) by country was estimated using the cost-benefit model and assumptions of (Woolf <i>et al.</i> , 2016) and global residue supply curves given by (Daioglou <i>et al.</i> , 2016), including revenue from sale of energy and from carbon credits but excluding impacts on crop yield.
	Soil organic carbon in croplands	Enhanced soil organic carbon sequestration by shifting from current management to no-till management with an input scenario consistent with cover cropping.	Adapted data from Soils Revealed (2020) which calculates the annual rate of change in soil organic carbon (SOC)/stocks based on Tier 1 stock difference approach (IPCC, 2019), to develop new estimates of technical potential and cost-effective potential (USD 100/tCO ₂ -eq) for croplands and grasslands. In this constrained cropping area, we assumed 90% adoption for the cost-effective potential at USD 100/tCO ₂ -eq (based on Griscom <i>et al.</i> [2017]).
	Soil organic carbon in grasslands	Enhanced soil organic carbon sequestration in managed pastures, by shifting from current practices to improved sustainable management with light to moderate grazing pressure and at least one improvement. For rangelands, a shift from current management defined by land degradation to nominally managed.	For grasslands, the technical potential was constrained to degraded grasslands and non-degraded grasslands (defined by GLASOD) were masked out due to lack of opportunity. We assumed 60% adoption to estimate cost-effective potential (<USD 100/tCO ₂ -eq) based on Griscom <i>et al.</i> (2017).

Source: Authors' own elaboration based on Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A. *et al.* 2021. Land-based measures to mitigate climate change: Potential and feasibility by country. *Global Change Biology*, 27: 6025–6058. <https://doi.org/10.1111/gcb.15873>

The selection of mitigation measures with their cost-effective mitigation potential allow to obtain activity units corresponding to the potential coverage of each mitigation measure with a carbon price of USD 100/tCO₂-eq. Activity units are expressed in hectares covered or number of animals affected by the mitigation measure. The fixed carbon price ensures that activity units reflect the relative feasibility of each mitigation measure compared to the others that are expressed in the same unit. For example, in Afghanistan, the number of hectares that would be cost-effective to reduce deforestation on is 247 per year, while for improved flooded rice

cultivation the number reaches 65 671 ha. This reflects a lower cost per unit of activity of improved flooded rice as compared to reducing deforestation in this specific example.

The relative feasibility of Implementing the activity at the given cost of up to USD 100/tCO₂-eq was then used to allocate aggregated costs to specific activities, whenever project's documents lacked sufficient granularity for constructing a precise cost split at the activity level as follows.

Step 1: The per unit cost is derived per each activity from the Roe *et al.* (2021) database. Using the example above, if avoiding deforestation on 247 ha costs up to USD 100, 1 ha of avoided deforestation will cost up to USD 100/247. Similarly, 1 ha of improved flooded rice will cost up to USD 100/65 671.

Step 2: Use the per unit of activity costs as “weights” in splitting aggregated costs:

Allocated cost of activity i = Aggregated cost / [Σ (per unit cost of activity i*activity i units impacted)] * (per unit cost of activity i* activity i units impacted).

Using example above, splitting costs of a USD 1 000 000 project implemented in Afghanistan focusing on the management of 10 000 of flooded rice and avoidance of deforestation on 100 ha, would be performed as follows:

Activity 1 = 100 ha.

Activity 2 = 10 000 ha.

Unit cost of activity 1 according to allocation key = 1/247.¹⁰

Unit cost of activity 2 according to allocation key = 1/65 671.

Budget to split = USD 1 000 000.

Expense on avoided deforestation = USD 1 000 000 / (1/247*100+1/65 671*10 000) * 1/247 = USD 726 682.

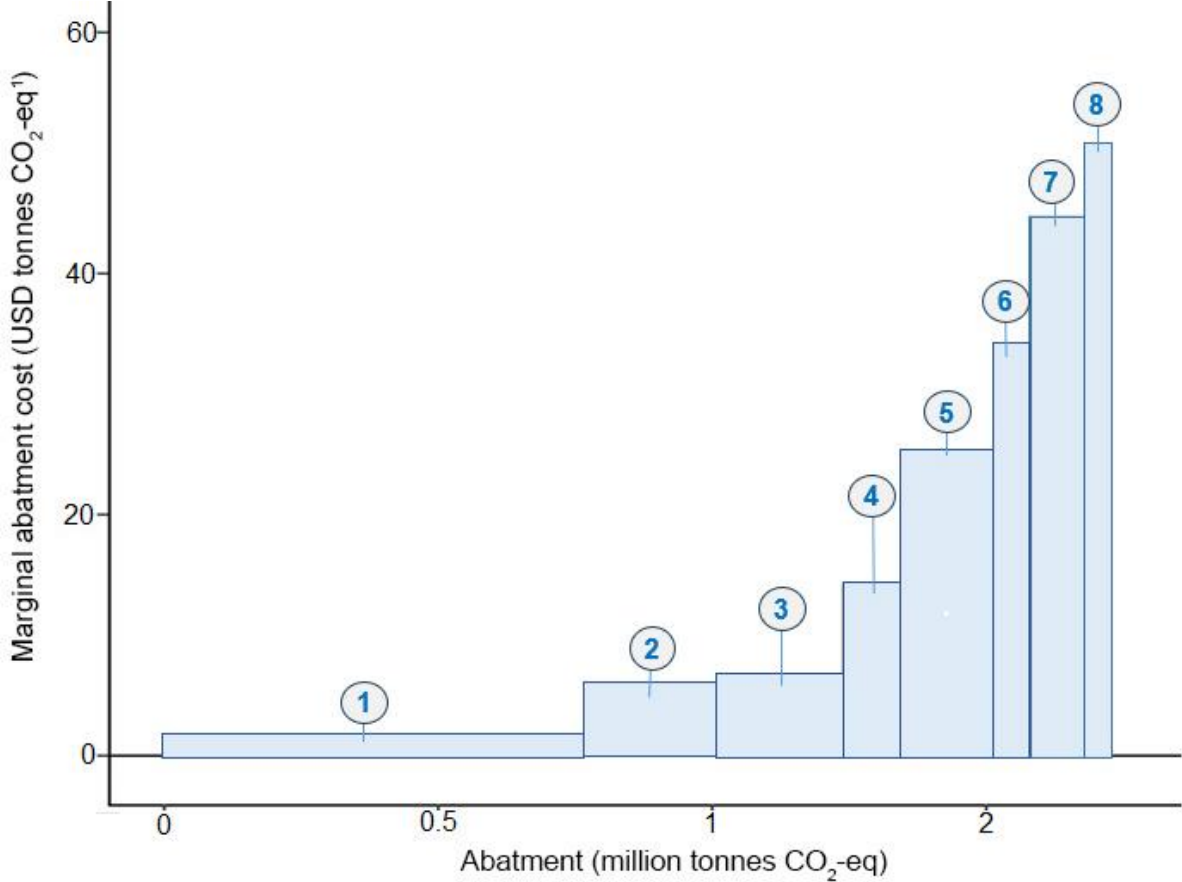
Expense on flooded rice management = USD 1 000 000 / (1/247*100+1/65 671*10 000) * 1/65 671 = USD 273 318.

¹⁰ The 100 in the numerator has been removed for simplicity of representation. It does not alter the calculations as all the 100 cancel each other out in the final calculations.

Annex 2. Marginal abatement cost curves real costs

This annex presents MACCs only for real costs that is it excludes the weighted costs calculated following step 4 of the methodology. The purpose of this exercise is to verify whether the distribution of activities follows a similar pattern when only real costs taken into account that is to somehow verify the validity of the allocation key applied. As MACCs based on real costs contain a smaller number of observations, that is it is a sub-set of the main sample, the categories of forest management, grassland degradation improvement and land use changes to annual cropland with subsequent management practices are not present in the respective graph.

Figure A1. Marginal abatement cost curve for the Global Agriculture and Food Security Program portfolio (real costs, 27 observations only)



- ① Afforestation
- ② Land use change to grassland and management practices
- ③ Land use change to agroforestry and management practices
- ④ Annual cropland manure application
- ⑤ Flooded rice improved practices
- ⑥ Improvements in agroforestry systems
- ⑦ Water management
- ⑧ Annual cropland improved soil management

Source: Authors' own elaboration.

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CONTACTS

Agrifood Economics and Policy Division – Economic and Social Development

ESA-Director@fao.org

www.fao.org/agrifood-economics

Food and Agriculture Organization of the United Nations
Rome, Italy

ISBN 978-92-5-138781-8 ISSN 2664-5785



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CD0779EN/1/05.24