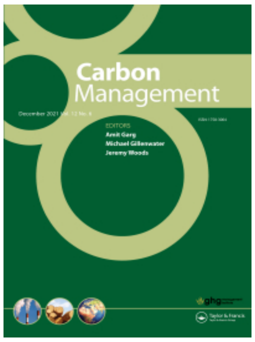

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RESEARCH ARTICLE

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Quantification of economically feasible mitigation potential from agriculture, forestry and other land uses in Mexico

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ABSTRACT

Countries often lack methods for rapidly, but robustly determining greenhouse gas (GHG) mitigation actions and their impacts comprehensively in the land use sector to support commitments to the Paris Agreement. We present rapid assessment methods based on easily available spatial data and adoption costs for mitigation related to crops, livestock and forestry to identify priority locations and actions. Applying the methods for the case of Mexico, we found a national mitigation potential of 87.88 million tons (Mt) CO_2eq yr^{-1}, comprising 7.91, 7.66 and 72.31 Mt CO_2eq yr^{-1} from crops, livestock and forestry/agro-forestry, respectively. At the state level, mitigation potentials were highest in Chiapas (13 Mt CO_2eq) followed by Campeche (8 Mt CO_2eq). Eleven states had a land use mitigation potential between 2.5 to 6.5 Mt CO_2eq, while other states had mitigation potentials of less than 2 Mt CO_2eq. Mitigation options for crops and livestock could reduce 60% and 6% of the respective emissions. Mitigation options for forestry could reduce emissions by half. If properly implemented, mitigation potentials on cropland can be realized with net benefits, compared to livestock and forestry options, which involve net costs. The method supports science-based priority setting of mitigation actions by location and subsector and should help inform future policy and implementation of countries' nationally determined contributions.

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Mitigation; GHGs; agriculture; forestry; land use; AFOLU; Mexico

Introduction

Agriculture and related land use change contributed about 23% of the world's anthropogenic greenhouse gas (GHG) emissions in 2016 (12.0 ± 3.0 Gt CO_2eq yr^{-1}) [1] and further expected increase in future as food production will need to increase to feed rising population [2]. Climate change mitigation in agriculture, forestry and other land use (AFOLU) is critical to achieving the 2 °C limit of the Paris Agreement [3]. Recent analyses indicate that land-based mitigation, which includes both carbon dioxide (CO_2) removal and GHG emission reduction, can contribute ~30% of the reductions needed to reach 2030 targets [4]. Despite its critical role in future emissions, action to reduce AFOLU emissions has lagged behind other sectors. Furthermore, land and its ecosystem management are critical for livelihoods in that they constitute the basis of net primary productivity, the supply of food and feed, fresh water, biodiversity and multiple other ecosystem services. Technological options for reducing GHGs through sustainable land management, together with enabling policies, are poorly understood. Specific, country-level recommendations for actions to increase sinks through improved land stewardship and reduced emissions from land use are generally lacking.

Mexico is one of the top-ten GHG emitters in the world and therefore has a significant role to play in reducing global emissions and determining the future climate. The AFOLU sector is responsible for 14.5% of total national GHG emissions in Mexico [5]. In Mexico's agricultural sector, methane (CH_4) and nitrous oxide (N_2O) emissions arise from livestock activities (enteric fermentation and manure management), as well as those from

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agricultural activities (soil management and field burning of crop residues). For land use, CO_2 emissions and removals are a result of changes in forest lands, pastures, agricultural land, wetlands and settlements [5]. The government of Mexico has included agriculture and other land uses as one of the priority sectors for GHG reduction in its Nationally Determined Contributions (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) [6]. Many practices in crop production, livestock and forestry management (e.g. enhanced nitrogen use efficiency, conservation agriculture, laser land levelling, biodigesters, enhanced manure management, zero deforestation and the role of carbon markets) can reduce GHGs emissions without compromising productivity. Spatial determination of emissions hotspots together with major contributors to emissions and identification of mitigation options and their potential help countries prioritize and incentivize mitigation actions based on their mitigation potential, cost of adoption, institutional capacity and market context consistent with their food security and environmental goals.

Here we present a rapid country-level assessment of some GHG mitigation options for the AFOLU sector in Mexico, together with the costs of their adoption. We also analyze the risks associated with adoption of proposed mitigation options and possible coping strategies. Science- and data-based estimation and mitigation potential help countries prioritize and incentivize mitigation actions based on their mitigation potential, cost of adoption, institutional capacity and market context consistent with their food security and environmental goal.

Methods

Analytical approach

The key starting point for assessing the mitigation potential of any economic sector is to quantify baseline emissions and analyze the major sources of emissions. Here, we employed a bottom-up approach using spatially explicit activity data for local production systems together with local soil and climate conditions to quantify baseline as well as business-as-usual (BAU) emissions. Mitigation potential can be estimated relative either to baseline emissions or to BAU emission scenario. In this analysis, we estimated mitigation potential relative to BAU scenario. For this we estimated GHG emissions under BAU and mitigation scenario for crop production, livestock production and the forestry and other land use (FOLU) sector and determined the mitigation potential for each sector as the difference in emissions under the BAU and mitigation scenarios. We then summed the sectoral estimates to obtain their combined mitigation potential. We analyzed emission and mitigation potential by jurisdiction (state level) because (i) activity data in Mexico are available for jurisdictions, (ii) ecological zones may vary by subsector and combining emission and mitigation data from all subsectors would be a challenge, and (iii) government decisions are taken at the jurisdiction level, so the jurisdiction-level mitigation potential will be useful for government action. Finally, we reviewed key policy documents and strategic plans to understand risks of adoption, institutional capacity, and the policy environment and to then suggest a possible roadmap for implementing mitigation options. See Sapkota et al. [7, 8] for similar analytical approaches.

Analysis

Data

We used activity data from year 2017 to estimate emissions from crop and livestock production and from 2015 for FOLU. See Supplemental Materials for crop, livestock and FOLU data sources. For the database under BAU and mitigation scenarios, we took baseline data and applied growth assumptions for factors such as input consumption, technological development, area under various land uses and livestock populations as well as adoption of various mitigation options as described in "GHG emissions scenarios" section.

GHG emissions from crop production

The same approach was used to determine spatially explicit emissions under baseline, BAU and mitigation scenarios, with mitigation potential calculated as the difference in emissions between the BAU and mitigation scenarios. GHG emission from crop production were estimated using the Mitigation Options Tool (CCAFS-MOT) of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) [9]. CCAFS-MOT combines several empirical models to estimate GHG emissions from different land uses and considers specific factors that influence GHG emissions, such as soil and climate, production inputs and management practices (See Feliciano et al. [9] and Sapkota et al. [8] for details).

GHG emissions from livestock production

Emissions from livestock production in Mexico were calculated according to the Guidelines for National Greenhouse Gases Inventories, Volume 4, Chapters 10 and 11 from the Intergovernmental Panel on Climate Change (IPCC) methodology [10]. We calculated emissions from enteric fermentation for dairy and beef cattle using a Tier 2 emissions factor developed for Animal under Grazing Management (AGM) (95.2 kg CH_4 head^{-1}yr^{-1}), Animal under Confinement Management (ACM) (126.23 kg CH_4 head^{-1}yr^{-1}) and Animal under Grazing-Confinement Management (AGCM) (99.86 kg CH_4 head^{-1}yr^{-1}). For swine production related emissions we used a developed country emissions factor (1.5 kg CH_4 head^{-1}yr^{-1}) for Intensive Production (SIP) system and developing country emissions factor (1.0 kg CH_4 head^{-1}yr^{-1}) for subsistence production system [10].

To estimate manure and manure storage (M&MS) emissions from dairy farming under AGM, we developed factors for CH_4 and N_2O emissions under grazing conditions and, for ACM under liquid, uncovered lagoon and biodigester conditions, according to the description in the INECC 2018 [11] national inventory. For AGCM we assumed 50% grazing and 50% confinement time, applying the emissions factors for CH_4 and N_2O developed for the other two groups.

To estimate M&MS emissions from beef under AGM, we developed CH_4 and N_2O emission factors for grazing conditions and, for ACM a factor for the same gases under dry lot and solid storage conditions, according to the description in the INECC national inventory. For AGCM we assumed 50% time under grazing and 50% under confinement and used the emissions factor for CH_4 and N_2O developed for the other two groups.

For M&MS emissions from swine under SIP, we developed CH_4 and N_2O emissions factors for pit storage, anaerobic lagoons and biodigesters, following the INECC description for the 2018 national inventory. For swine under Familiar Production, we developed emissions factors for CH_4 and N_2O under grazing conditions.

The baseline scenario models and assumptions underlying calculations of FOLU emissions and removals are based on the 2006 IPCC Guidelines for the National Greenhouse Gas Inventory, under the approach "Stock differences." The activity data for the baseline calculation includes a group of unbiased statistical estimates for each IPCC category and sub-category of land use, which were derived from uncertainty assessments carried out using other data from the geospatial union of the original inputs (Series II, III, IV, V and VI of the National Institute of Statistics and Geography (INEGI) on the land use and vegetation chart, scale 1:250,000).

Certain statistical estimates lack geographical explicitness; that is, the data are spatially referred but not spatially explicit. The Comisión Nacional Forestal (CONAFOR) has carried out this process for the entire country including Campeche, Chiapas, Jalisco, Oaxaca, Quintana Roo and Yucatán. We obtained baselines for the other 26 states of Mexico by subtracting national emissions from available states and multiplying those values by the percentage of forest area for each state relative to the total forest area of the remaining 26 states.

After all GHGs (CO_2, CH_4 and N_2O) were calculated, they were converted into CO_2eq using global warming potentials over 100 years of 34 and 298 for CH_4 and N_2O, respectively [12].

Crop production mitigation options, costs and benefits

Crop-production-related mitigation options were derived from literature review, through stakeholder consultations carried out in El Batan, Mexico and expert opinions. For example, in high input cropping areas, farmers apply nitrogen (N) fertilizer at supra-optimal rates resulting into low N use efficiency (NUE; defined as crop N harvested relative to N input) and substantial excess N leached or emitted to environment. Improving NUE through adoption of various precision nutrient management technologies would lower N_2O emissions [13] in such production environment, while helping to reduce fertilizer rates without compromising yield, so these technologies were considered important mitigation options.

Conventional tillage tends to promote soil carbon (C) losses through enhanced decomposition and erosion of soil organic matter. Zero-tillage, a key component of conservation agriculture, often increases soil C stock, although the permanence of C sequestered this way is questionable [14]. The potential of C sequestration through adoption of zero-tillage were estimated using tillage factors for different climate zones [15]. Furthermore, reduced energy requirements due to minimum or non-requirement of tillage under reduced or zero-tillage are linked to savings in fuel, which was taken from CIMMYT's experimental data in Obregon research station. Precision levelling of crop fields can help to lower GHG emissions by reducing cultivation time and improving the efficiency of fertilizer and irrigation water. Therefore, emission reductions from the adoption of land levelling were calculated indirectly by estimating savings in cultivation energy, fertilizer and irrigation.

Livestock production mitigation options, costs and benefits

Mexico's NDC for livestock includes farm biodigesters and recovered grazing areas [16]. This study did not consider mitigation options for recovered grazing areas because related actions are not well documented and activities under the IPCC Guidelines for National Inventories do not include mitigation for livestock. We estimated mitigation potential of farm biodigesters for dairy and swine according to technical indications from FIRCO-SAGARPA [17] and for intensive production based on data from the national inventory report [11]. To establish the need for a biodigester, we considered technical conditions and the minimal number of farm heads required to generate electricity, in accordance with Eaton et al. [18]. Biodigester costs included the purchase of generators and related equipment. We included composting plant for beef production with manure management under dry lot and solid storage. Cost data and technical parameters were according with Granollers [19].

FOLU mitigation options and costs

The potential beneficiary population for the FOLU mitigation option represents the number of people living in areas with forest conservation, protection and restoration activities established in Mexico between 2010 and 2017 through the CONAFOR programs and from 2019 and 2020 through the "Sembrando Vida" program of the Secretaría de Bienestar. Therefore, the Mexican government has already delivered financial and in-kind subsidies to farmers to establish these areas. To obtain certification, owners and holders of forests and preferably forestlands for conservation, restoration and forest management actions are expected to show C sequestration potential and results through the related projects that meet a national or international standard.

The main implementation costs for FOLU mitigation measures are for developing national capacities, paying for technical advice, establishing site-level monitoring, reporting and verification systems (MRV) and contracting external verification services. Certified owners and holders of the benefited lands are expected to offer offsets in C markets, thereby adding to NDCs while diversifying and improving their incomes.

GHG emissions scenarios

We estimated GHG savings through various options against 2030 BAU emissions, which were estimated based on AFOLU sector growth assumptions for factors such as input consumption, technological development, area under various land uses and livestock populations. These expected changes were validated through expert consultation and a stakeholder workshop.

Business-as-usual scenario. The BAU scenario for cropland considered that over the last 10 years, N fertilizer use increased 48% [20] and maize production increased by 28%. Extrapolating N fertilizer use to 2030 gave an expected increase of 50% over 2017 levels. Analyzing this trend and the expected food deficit (projected demand minus projected production) for 2030 gave an expected increase in N fertilizer use of 50% in irrigated and high-rainfall rainfed areas and of 20% in low-rainfall rainfed areas with dry climates. In areas where current N fertilizer is equal to or greater than 400 kg ha^{-1}, we assumed no increase. The projected N fertilizer use trends were applied in maize, wheat and sugarcane production.

The government of Mexico has introduced a price support program to protect farmers from market failures that incentivize increasing the area under crops, as well as the "Sembrando Vida" program which encourages farmers to dedicate land for forestry, agro-forestry and "milpa," the traditional maize-bean-squash intercrop. Based on these factors, we assumed a 7% increase in maize area. Based on the stability of Mexico's wheat area since 2004, we assumed no change in wheat area to 2030, whereas the area under sugarcane has increased 25% during 2004-2018 and is expected to increase from 10-15% between now and 2030, so we assumed a 12.5% increase of sugarcane area between now and 2030 in sugarcane producing states.

We estimated the BAU scenario for livestock using historical information about animal populations, production and weights from Agroalimentary Information System (SIAP, Sistema de Información Agroalimentaria y Pesquera) database [21]. For cattle's BAU, we considered 2011-2020 projections for the agri-food sector from the agriculture ministry [22] and for swine, pig production projections [23]. Historical information was used to identify drivers and Average Annual Growth Rate (AAGR) for swine, dairy and beef. The AAGR were used for BAU and to estimate total livestock GHG emissions to 2030.

The BAU scenario for FOLU assumes that no new measures will be implemented to mitigate climate change and that recorded emission/removal trends will continue as reported in the INEGYCEI_USCUSS 6a_CN [5]. The scenario was developed in four steps: (i) collection and systematization of historical area information; (ii) future projection of areas using statistical models and/or explanatory variables (drivers); (iii) projecting parameters and emission factors to 2050; and (iv) estimating projected emissions and removals to 2050 [11]. The BAU scenario was projected to 2050, even though our sources report the estimated emission and removal values to 2030. BAU scenario to 2030 was taken from developing implementation pathways for the NDCs to greenhouse gas and compounds mitigation in the land use and forestry sector.

Mitigation scenario. To estimate emissions under the mitigation scenario, we applied all possible mitigation options and their mitigation potential, together with the scale of their adoption, over the BAU scenario. For high-input areas of Mexico where farmers over-apply N fertilizer and much N is lost, we calculated plot-level NUE using yield and applied N, assuming respective N contents of 1.58% and 1.99% for maize and wheat grain and 0.13% for sugarcane stalks [9]. For all areas where NUE was less than 50%, the optimum N rate was estimated assuming NUE of 50% following the equation below.

$$\text{Optimum N input (kg N/ha)} = \text{kg N removed at harvest/NUE (50\%)}$$

where

$$\text{kg N removed at harvest} = \text{crop yield } \left(\text{kg}^{-1}\right) * \text{crop moisture } (\%) * \text{average N content } (\%)$$

Where NUE was <50%, we calculated balanced N to raise NUE to 50%; where NUE was >50%, we added N to increase yield by 20%. The N balance thus calculated was used to modify input data and emissions under the mitigation scenario.

Similarly, the area under conservation agriculture for maize, wheat and sugarcane in the mitigation scenario was estimated to be 80,000, 10,000 and 10,000 ha, respectively. We speculated that conservation agriculture will be adopted mainly in the states of Chiapas, Guanajuato, Guerrero, Hidalgo, Jalisco, Sonora and Michoacán. The estimated crop area under precision levelling, about 30% at present, is projected to increase by 40% and 50% under the BAU and mitigation scenarios, respectively.

Livestock facilities are a key factor for emissions estimates in the mitigation scenario. To project adoption of biodigesters, we did not consider AGM, family or beef production. We also set a minimum animal population for a biodigester to produce energy. To estimate the benefits of composting in beef production, we considered the numbers of heads under dry lot and solid storage manure management, along with the number of heads required to produce one ton of manure per day, following Granollers [19].

To estimate the mitigation benefits of changing from anaerobic lagoons to biodigesters, we developed and compared Tier 2 emission factors by state and municipality for both technologies. Similarly, to estimate mitigation benefits of adopting a composting plant, we developed and compared Tier 2 emission factors for solid storage and composting. Finally, for each technology we considered maximum mitigation potential, based on technical necessities and livestock data in the 2017 national agricultural survey [24].

In the forestry and other land use, Government of Mexico has set three goals, i.e. zero percent net deforestation by 2030, sustainable forest management and management of natural protected areas (Àreas Naturales Protegidas, ANP) to reduce GHG emissions. Associated objectives and courses of action for these goals are summarized in Table S1. The mitigation potential of these three goals has been evaluated by INECC up to 2050, based on the results of two public policy initiatives: (i) the National REDD + Strategy, which targets 0% deforestation by 2030, and (ii) the National Strategy for Sustainable Forest Management to Increase Production and Productivity, 2014–2018, which sought to raise total biomass stocks under sustainable forest management ecosystems.

As part of this study, a new mitigation strategy was added to the preceding three goals: including the Mexican forestry sector in C markets. We followed a traditional empirical model to design the requisite public policies, based on an analysis of strengths, weaknesses, opportunities and threats

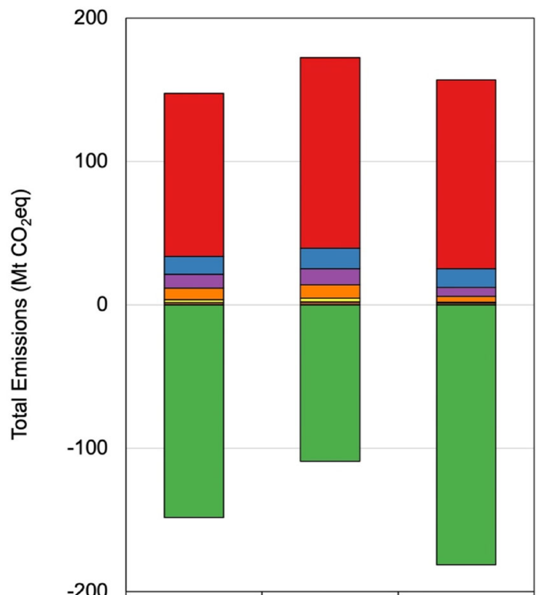
(SWOT; see Annex FOLU S1). Based on the analysis, we identified the following populations as the basis for estimating C capture (CONAFOR 2015):

1. *Potential population:* population representing the need or problem addressed in the program objectives, which could therefore be eligible for its attention. For the purposes of this project, hereafter referred to as "potential area."
2. *Target population:* potential population zone that requires more urgent and strategic attention.
3. *Population served:* target population attended by the program per year based on available resources.

To estimate mitigation potential, we calculated C stocks in aboveground and underground biomass managed by the population served, using the IPCC "Differences in stocks" approach with the IPCC emissions formula = *(Activity Data)*(Emission Factor)*. This approach requires calculating C stocks at least twice: once for the year in which the area is incorporated into the program and once for 2030. The difference between the two represents the associated mitigation potential.

The emission factors and maximum C densities are specific to the country's ecosystems and developed by the Specialized Technical Unit for Monitoring, Reporting and Verification of the National Forestry Commission for the INEGYCEI compilation from 1990 to 2015. To estimate the mitigation potential of this, we set up a series of assumptions for the three populations described above to determine C stocks at the moment each population enters the program and for 2030 (Annex FOLU S1). The mitigation potential of each option equals the difference in emissions under the BAU and mitigation scenarios.

The mitigation potentials of various mitigation options were combined to obtain the mitigation potential of state-level mitigation packages. This calculation was strictly additive; we did not attempt to calculate possible synergies. The costs and/or benefits of adopting mitigation options were calculated using the unit prices of adoption-related inputs and outputs, using current market prices in Mexico for commodities such as fertilizer, fuel, electricity and harvested products.



	Baseline	BAU	Mitigation
Beef cattle	113.74	132.98	131.65
Dairy cattle	12.34	14.28	13.13
Maize	9.58	11.15	6.04
Pig	8.21	9.43	4.24
Sugarcane	2.07	2.62	0.60
Wheat	1.52	1.99	1.22
FOLU	-148.35	-108.96	-181.27

Figure 1. Contribution of various crops, livestock species and FOLU to total emissions/sequestration for the baseline (2017 for crop and livestock production and 2015 for FOLU sector), and for 2030 under the business-as-usual (BAU) and mitigation scenarios.

Results and discussion

Total emissions

Crop and livestock emissions

Based on this rapid analysis, we estimated total emissions from crop and livestock production in Mexico at about 147.45 Mt CO_2eq and C sequestration from the FOLU sector of about 148.35 Mt CO_2eq, resulting in a net sequestration of about 0.90 Mt CO_2eq (Figure 1). Crop and livestock production respectively accounted for 9% and 91% of total agricultural emissions. Figure 1 shows total national emissions from crop and livestock and total sequestration from FOLU sector together with the contribution from major crops and livestock species. State-wise emission from crop, livestock and sequestration for FOLU sector together with the combined effect of crop, livestock and FOLU is shown in Figure 2a.

Crop production in Mexico accounted for some 13.17 Mt of CO_2eq in 2017 (Figure 1). This is similar to reported crop production emissions in 2015 (16 Mt CO_2eq) [25]. Total emissions from crop production were highest in Jalisco (11.5%) and Sinaloa (11.24%), followed by Veracruz (9.5%) and Michoacán (8.63%). Maize contributed over 72% of total crop-related emissions, followed by

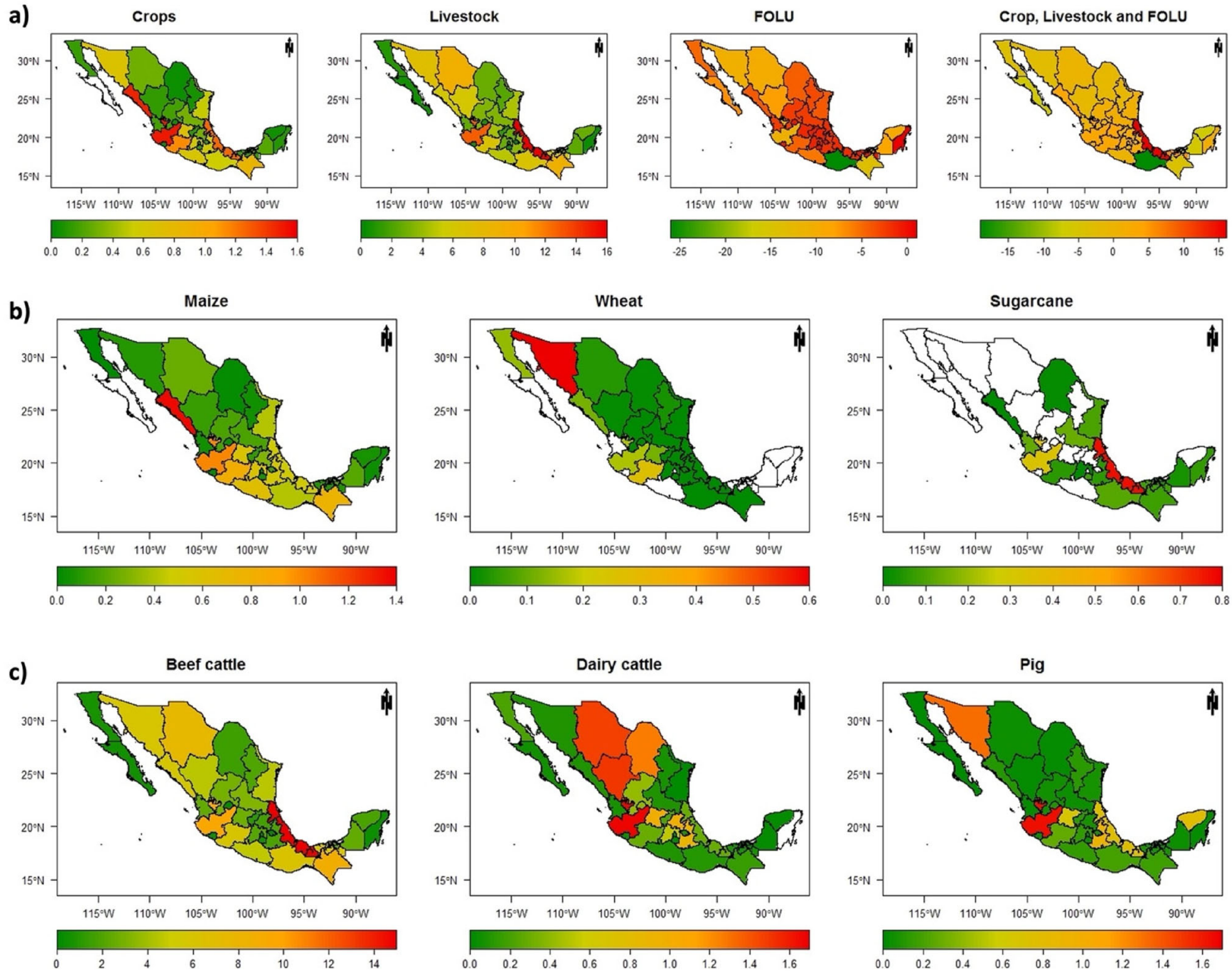


Figure 2. **State-wise distribution of (a) total GHG emissions/sequestration (Mt CO_2eq) from crops, livestock, FOLU and combined effect of crop, livestock and FOLU sector, (b) GHG emissions (Mt CO_2eq) from maize, wheat, and sugarcane, and (c) GHG emissions (Mt CO_2eq) from beef cattle, dairy cattle, and pig. No color means calculations were not done due to lack of activity data.**

sugarcane (15%) and wheat (11%). Emissions from maize production were highest in Sinaloa, characterized by larger-scale commercial maize farms, followed by Jalisco and Michoacán (Figure 2b). Maize-related emissions were also high in maize-growing states such as Chiapas, Guerrero, Guanajuato, Mexico, Puebla, Veracruz, Tamaulipas and Oaxaca. The state of Sonora was responsible for about 39% of wheat-related emissions, followed by Michoacán (17%), Jalisco (11%) and Baja California (9%). Emissions from sugarcane were highest in Veracruz (37%), followed by Jalisco (16%); other states together accounted for less than 7% of sugarcane-related emissions.

Emissions from livestock production in 2017 were estimated at 134.29 Mt CO_2eq (Figure 1), almost double the reported value in Mexico's sixth National Communication for the year 2015 (85.29 Mt CO_2eq) [5]. Major emitters were the states of Veracruz (11.8% of total livestock emissions), Jalisco (9.1%), Chihuahua (6.8%) and Chiapas (6.8%) (Figure 2c). Beef production accounted for the bulk of total emissions from livestock, contributing 113.74 Mt CO_2eq. Livestock emissions under the BAU scenario are projected to reach 156.69 Mt CO_2eq by 2030. Implementation of mitigation efforts, including composting plants for beef production and biodigesters for dairy and swine would reduce total livestock emissions in 2030 to 149.02 Mt CO_2eq; 9.5% less than under the BAU scenario (Figures 1 and S3).

Total emissions in FOLU. In 2015, emissions from the FOLU sector were 20.26 Mt CO_2eq and sequestration of 168.61 Mt CO_2eq, resulting in a net balance of −148.35 Mt CO_2eq (Figure 1). Buira et al. [26] and Dittmer et al. [27] report similar levels of C sequestration in the FOLU sector at 139 and 148 Mt CO_2eq, respectively, in 2015. The net absorptions of the FOLU sector offsets 22% of Mexico's total emissions. Chiapas had the highest emission intensity (5.03 Mt CO_2eq) for this sector and Quintana Roo the highest sequestration (-27.25 Mt CO_2eq). The five states with the most favorable highest net balance (capture minus emissions) were Oaxaca (-25.81 Mt CO_2eq), Chiapas (-13.87 Mt CO_2eq), Jalisco (-10.72 Mt CO_2eq), Sonora (-10.50 Mt CO_2eq) and Chihuahua (-9.62 Mt CO_2eq) (Figure 2a).

The trend scenario or BAU suggests the FOLU sector will continue to provide an important CO_2 sink through 2050, though it will diminish from an average 128 Mt CO_2eq of sequestration during 1993-2013 to 108.96 Mt CO_2eq by 2030 (Figure 1) and 91 Mt CO_2eq by 2050 (Figure S4). Our estimated mitigation potential in FOLU sector is much higher (47.96 Mt CO_2eq additional mitigation potential than governmental target) than the mitigation goals of Mexican government, i.e. −31.37 Mt CO_2e [11], −16.60 Mt CO_2eq and −0.09 Mt CO_2eq for the 0% deforestation target rate, increasing C stocks and management of ANP, respectively (Figure S5).

Technical and economic mitigation potential

Under the BAU scenario with no mitigation, GHG fluxes from crop and livestock production are projected at 172.45 Mt CO_2eq by 2030, while the FOLU sector is expected to capture 108.96 Mt CO_2eq, resulting in net emissions of 63.49 Mt CO_2eq yr^{-1} from the AFOLU sector (Figure 1). Emissions from crop and livestock production under mitigation scenario are estimated at 156.88 Mt CO_2eq, with a GHG capture by the FOLU sector of 181.27 Mt CO_2eq, resulting in net negative emissions; that is, 24.39 Mt CO_2eq would be sequestered each year. Thus, the assumed levels of adoption of the mitigation options identified for crop and livestock production and the FOLU sector in Mexico would result in a total mitigation of 87.88 Mt CO_2eq yr^{-1} (Figures 1 & 4), comprising 7.91, 7.66 and 72.31 Mt CO_2eq yr^{-1} from the crop, livestock and FOLU sectors, respectively. Among crop and livestock production, maize and swine offered the highest technical mitigation potential – nearly 5 Mt CO_2eq yr^{-1} component^{-1} – and wheat production offered the least mitigation potential. Buira et al. [26] show crop, livestock and land use emissions of approximately 20, 60 and −150 Mt CO_2eq in 2030 based on the deep decarbonization pathway that identifies a set of sectoral trajectories potentially consistent with meeting the Paris Agreement.

Total mitigation potential from AFOLU sector was the highest in Chiapas (∼13 Mt CO_2eq) followed by Campeche (∼8 Mt CO_2eq) (Figure 3a). Eleven states (i.e. Oaxaca, Quintana Roo, Yucatan, Jalisco, Sonora, Veracruz, Durango, Chihuahua, Puebla, Michoacán and Guerrero) had total AFOLU mitigation potential between 2.5 to 6.5 Mt CO_2eq, other states have AFOLU mitigation potentials of less than 2 Mt CO_2eq.

Figure 4 shows the magnitude of GHG savings per year through adoption of various mitigation measures from the AFOLU sector in Mexico together with the abatement cost per unit of CO_2eq abated. Many of the mitigation measures employ currently available technologies and can be implemented immediately. The cost-beneficial measures have negative cost and appear below the x-axis on the left-hand side of the graph, whereas the cost-incurring measures appear above the x-axis, on the right-hand side of the graph. Of the total technical mitigation potential of 87.88 Mt CO_2eq yr^{-1}, about 6.33 Mt CO_2eq was accounted for by measures that have a cost saving associated with adoption.

The crop production sector in Mexico has a total mitigation potential of about 7.91 Mt CO_2eq yr^{-1} with the additional benefit of 19.41 billion MXN. Crop mitigation potential was the highest in Veracruz, Jalisco and Michoacán and intermediate (between 0.4 to 0.6 Mt CO_2eq) in the states of Chiapas, Sinaloa, Guanajuato, Mexico and Guerrero (Figure 3b). Other states had crop mitigation potentials of less than 0.4 Mt CO_2eq. GHG mitigation in the crop sector could be obtained through better N management, preventing crop residue burning and adoption of conservation agriculture and laser land levelling. In crop production, better N management to improve NUE contributes the highest mitigation potential (∼6 Mt CO_2eq) followed by prevention of crop residue burning (∼1.57 Mt CO_2eq), whereas adoption of conservation agriculture and laser land levelling provide nominal mitigation potential (Figure 4). Adoption of these mitigation packages (i.e. improved NUE, prevention of residue burning, adoption of conservation agriculture and laser land levelling) in five major states of Mexico (i.e. Veracruz, Jalisco, Michoacán, Chiapas and Sinaloa) would deliver about 50% of total crop production related mitigation potential. Mitigation effect of better N management was highest in the states of Jalisco, Michoacán, Sinaloa, Veracruz and Chiapas whereas that of preventing residue burning was the highest in Veracruz, Jalisco, San Luis Potosi, and Oaxaca.

Total mitigation potential for livestock is 7.66 Mt CO_2eq yr^{-1} and with the estimated investment of

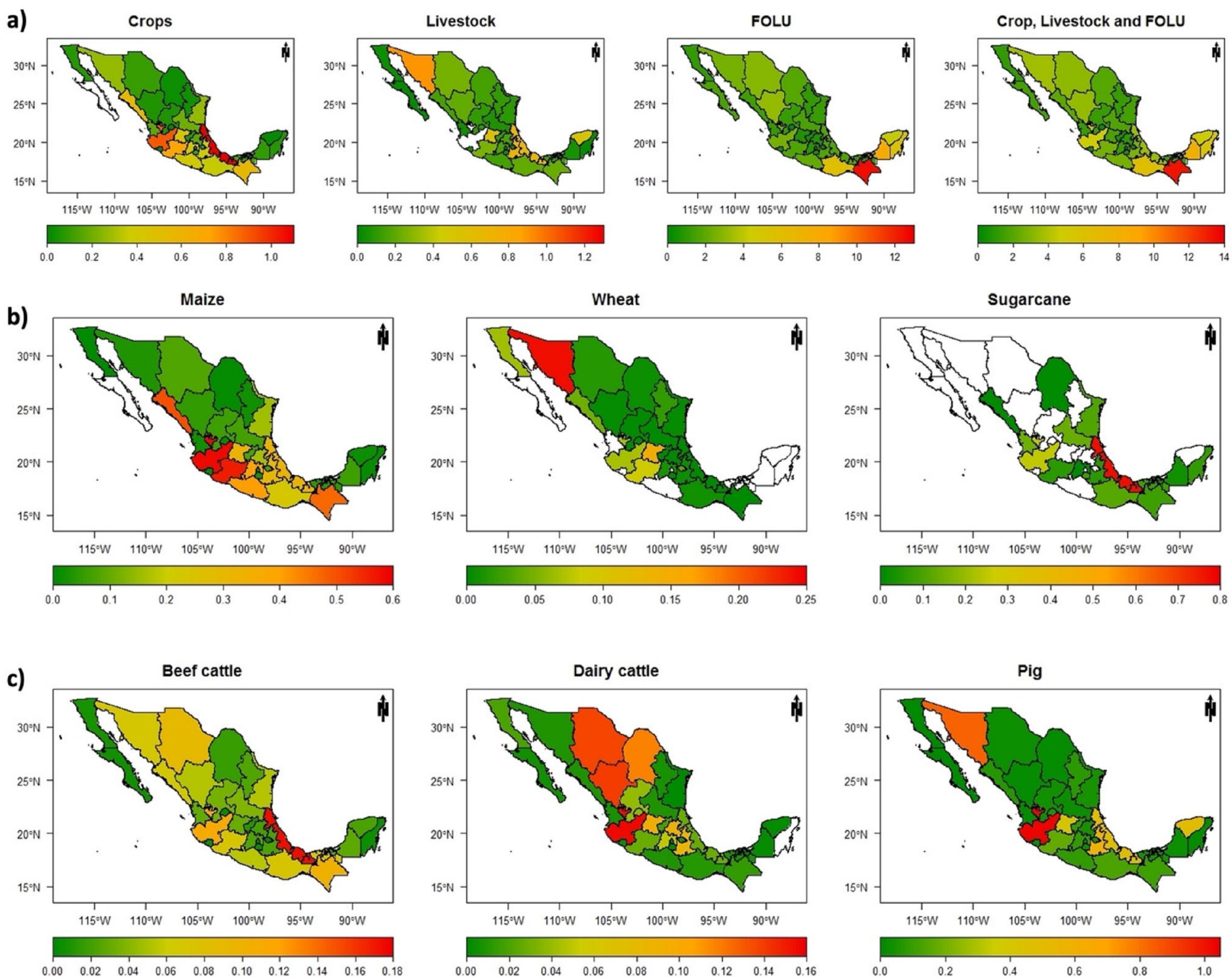


Figure 3. State-wise distribution of GHG mitigation potential (Mt CO_2eq) from (a) crop, livestock, FOLU and combined effect of crop, livestock and FOLU sector, (b) maize, wheat, and sugar cane, and (c) beef cattle, dairy cattle, and pig. No color means calculations were not done due to lack of activity data.

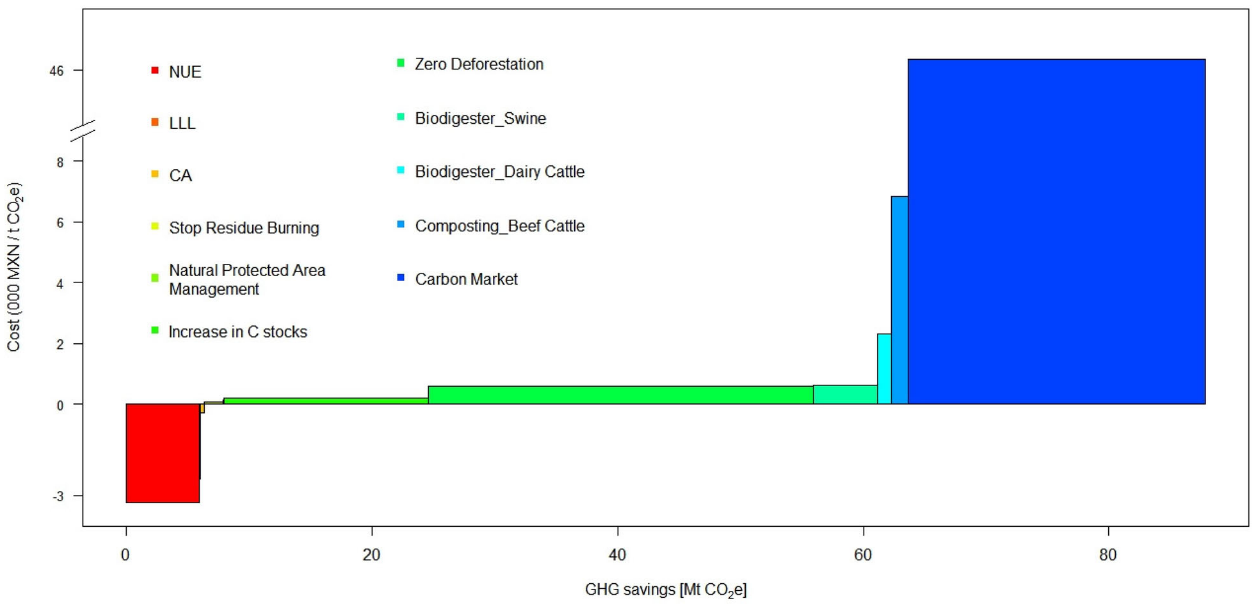


Figure 4. Marginal abatement cost curve for AFOLU sector in Mexico. The width of the bar represents the abatement potential from the mitigation option whereas height of the bar represents the average cost per unit of CO_2eq abated. The area (height*width) of the bar represents the total cost of the action, i.e. how much it would cost altogether in order to deliver all of the CO_2eq savings from the action. NUE = nitrogen use efficiency; LLL = laser land levelling; CA = conservation agriculture.

14.92 billion MXN. Livestock mitigation potential was the highest in Jalisco and Sonora and intermediate (between 0.4 to 0.8 Mt CO_2eq) in the states of Puebla, Veracruz, Guanajuato, and Yucatan. Other states have livestock mitigation potentials of less than 0.3 Mt CO_2eq (Figure 3c). The highest potential options found that the use of biodigesters on swine farms had the potential to mitigate 5.18 Mt CO_2eq. 1,364 installed biodigesters with a capacity to receive liquid manure from 5,500 adult animals are necessary. Biodigesting of dairy cattle manure and composting of beef cattle manure together would have a total mitigation potential of about 2.5 Mt CO_2eq yr^{-1} with a total investment requirement of 11.72 billion MXN. While several options exist for reducing livestock emissions (i.e. improved breeding and feeding, feed additives, grazing and pasture management, manipulation of rumen), the impacts are not always easy to estimate, can be highly context dependent or may not be an option as cost remains a barrier [28, 29].

The FOLU sector has a total mitigation potential of 72.31 Mt CO_2eq yr^{-1} to 2030 with an estimated investment of 23.82 billion MXN. The highest mitigation potential from the FOLU sector was estimated to be from Chiapas and followed by Campeche, Oaxaca and Quintana Roo (Figure 3a). The highest mitigation potential in the FOLU sector comes from a zero-deforestation program (31.36 Mt CO_2eq yr^{-1}) followed by a C offset in the C market (24.26 Mt CO_2eq yr^{-1}). However, mitigation through C offset in the C market was estimated to have the highest abatement cost (Figure S4). The five states with the greatest mitigation potential under an intermediate C market scenario (considering that it is the most likely) are Quintana Roo (-2.68 Mt CO_2eq), Chiapas (-2.25 Mt CO_2eq), Campeche (-1.54 Mt CO_2eq), Veracruz (-1.44 Mt CO_2eq) and Durango (-1.43 Mt CO_2eq).

These estimates should be interpreted in light of uncertainties associated with activity data, emission factors and models used in the Cool Farm Tool. Similar studies [7], calculated 95% confidence interval as a measure of uncertainty due to activity data such as crop or livestock management practices. Given the use of census data for crop area, livestock populations, farm management and corresponding soil and climatic information in this study, we believe that the level of uncertainty in our estimation is greatly reduced. Further, result of this rapid analysis should be used as decision support rather than as a precise and definitive predictor of GHG emissions and mitigation potential.

Emission reduction potentials relative to Mexico's NDC target

To help meet the target of maintaining global warming at or below 2 °C above pre-industrial level, Mexico's estimated GHG reduction in agriculture will need to be 7-18% of 2030 emissions. Based on this analysis, crop and livestock sector mitigation options could reduce emissions within sectors by 60% and 6%, respectively. Similarly, mitigation options in the FOLU sector will result in a reduction of an additional 50% of the sectoral GHG reduction.

Institutional capacity and risks/barriers to adoption of mitigation options

For wheat and maize, irrigated and high-rainfall areas – which typically feature more intensive use of inputs, including N fertilizer – offer the best mitigation opportunity through better N management and particularly, given the low NUE in such cropping areas, for moderating N application rates to reduce N_2O emissions without affecting yields [13, 30] or national food security targets. Marketing and price support to maize and wheat farmers ("Programa de Apoyos a la Comercialización," which farmers in irrigated and high-rainfall areas received) from previous federal administrations had no strings attached. Targeted subsidies to the farmers following sustainable and climate-responsive practices under the new national development plan (Plan Nacional de Desarrollo) could be conditioned to push farmers to apply new technologies for improved NUE, conservation agriculture or land levelling.

Biodigesters represent an excellent option to reduce emissions from manure on livestock farms [18]. Mexico has an official supplier and the capacity to install biodigesters; 461 were installed between 2010 and 2014 [5]. However, there is currently no official program or financial support for any mitigation option for the livestock sector. On some farms, biodigesters have been so successful that additional ones have been installed; in contrast, failed cases have represented a big problem in farm operations, and this has typically resulted from inadequate maintenance and the need for specialized operators.

The mitigation potential of sequestration in Mexico's forestry sector was estimated for high-end (54.88 Mt CO_2eq), intermediate (24.26 Mt CO_2eq) and low-end scenarios (15.86 Mt CO_2eq). At current market price of C sequesstion, i.e. USD 10 tCO_2eq^{-1}, the values of capture and sequestration in Mexico's forestry sector under the above scenarios would approximate USD 549 million (high-end), USD 243 million (intermediate) and USD 159 million (low end).

For the National Forest Program, CONAFOR spent a budget of USD 1.88 million for January 2013 through September 2018 and the Secretaría de Bienestar plans to allocate USD 0.786 million for the Sembrando Vida program in 2019. Similar levels of expenditure are expected in 2020. The funds were allocated, among other things, for forest conservation, restoration and exploitation in areas inhabited by potential beneficiary populations. Although the Mexican government allocated this funding for purposes not directly related to climate change mitigation, the activities in fact provide this environmental service.

The additional public funding needed to achieve the aforementioned forestry sector mitigation outcomes would be on the order of USD 71 million (high-end), USD 59 million (intermediate) and USD 47 million (low-end) and would cover 100% of the expenses associated with technical assistance (C1), baseline inventories (C2), georeferencing (C3), and initial external supervision (C4). Comparing costs versus expected revenues from C sales, mitigation measures appear profitable.

Priorities of the current national government do not align with actions to meet either the three previously-set official mitigation goals for FOLU in Mexico or the new measure proposed in this study, and in fact have constrained the provision of human, material or financial resources to institutions viewed as addressing "non-priority issues" such as meeting NDC goals. Current political discourse provides no clear indication of whether or not the programs established to comply with the national goals are currently enforced. Emerging policy directions appear to favor support for community forest development, which in theory will raise productivity, but the lack of clarity regarding the validity and continuity of the original strategies raises questions about the possible fulfilment of the related goals.

For the new mitigation activity, technical and financial barriers are identified, since it will be necessary to develop national capacities at all levels in all sectors (professional, official, academy, etc.) to support development of C projects that meet the chosen standards, as well as having access to funding for technical assistance, the MRV systems, external supervision and the operating costs of the standard. In any case, Mexico has extensive experience in using subsidies for technical studies and forest certification. The fact that C titles are traded abroad represents both a risk and an opportunity to strengthen forestry relative to other competing land use activities. Incentives for deforestation by target users encourage them to participate in programs such as "Sembrando Vida" is another risk.

Recommendations

Irrespective of cost-effectiveness, realization of estimated mitigation potential depends on the adoption of the mitigation options to the extent assumed under mitigation scenarios. Based on the costs used here, public finance, incentive mechanisms will be necessary to realize those targets. The states with high FOLU or livestock mitigation potentials, e.g. Jalisco and Chiapas, respectively, should incentivize the adoption of mitigation options through appropriate policy interventions. To identify the feasibility of actions, the next step would be to engage policy makers and stakeholders in priority states.

In the states with high mitigation potentials, the government has a range of options to encourage wider adoption of the identified mitigation options and realization of mitigation potential. Activities identified as part of mitigation for the crop production sector include: (i) in the case of N, avoid fertilizer subsidies, since those tend to result in inefficient use of N. N use could be reduced without compromising yield through policy by providing subsidies to farmers that adopt more efficient N management practices; (ii) in land levelling, provide a subsidy as an incentive for the adoption of this technology, which in addition to reducing GHG emissions should increase productivity; and (iii) in conservation agriculture, also through policy, provide subsidies to farmers that adopt this technology. Particularly in rainfed areas, the adoption of this technology will result not only in a reduction of GHG but also will improve productivity.

Mitigation options identified in the livestock sector include: (i) create official program and financial support; (ii) training and articulation between environmental and agriculture government institutions and stakeholders; (iii) correct design and maintenance according to farm; and (iv) articulation to the energy sector.

Lastly FOLU sector mitigation options identified include: (i) ensuring that the forestry sector is within the sectors approved by the Mexican Emissions Trading System (ETS); (ii) conducting capacity development at all levels in all sectors (professional, official, and academic); (iii) strengthening and concluding the NMX-173 Mexican regulation commissioning process in all its components to make it operational and (iv) including support programs within CONAFOR subsidies for developing C forest projects, including costs for technical assistance and external supervision.

Conclusions

This study used minimal and readily available country-specific spatial data to produce a rapid analysis that enabled prioritization of AFOLU mitigation options at the subnational jurisdictional level. This is an improvement over existing country emissions inventory that were based on emission factors and activity data. Our results show substantial mitigation potential of ~88 Mt CO_2eq in 2030 in the AFOLU sector, which is about 12.5% of the total GHG emission in Mexico. To demonstrate this, other studies have showed AFOLU mitigation potentials in 2030 of 33.3 Mt CO_2eq in Thailand (10.6% of total national emissions in 2013) [31] and 19.6 Mt CO_2eq in Nepal (36.3% of total national emissions in 2011) [32] at the highest carbon price of $500 per t CO_2eq. Hoa et al. [33] showed a mitigation potential of 48 Mt CO_2eq yr^{-1} (14.9% of total national emissions in 2014) in Vietnam in the case of full application of countermeasures (i.e. best technical practices) in 2030.

The state-wide and total magnitude of mitigation was the highest from the FOLU sector (~72 Mt CO_2eq) relative to the agriculture sector across Mexico, albeit at higher abatement cost. At the state level, AFOLU technical mitigation potentials were highest in Chiapas (~13 Mt CO_2eq) followed by Campeche (~8 Mt CO_2eq), indicating that these states are priorities for mitigation based on overall technical impacts. An additional 11 states (Oaxaca, Quintana Roo, Yucatan, Jalisco, Sonora, Veracruz, Durango, Chihuahua, Puebla, Michoacán and Guerrero) were identified as medium priority with mitigation potentials of 2.5 to 6.5 Mt CO_2eq. The remaining 19 states were low priority, having mitigation potentials less than 2 Mt CO_2eq. However, only cropland mitigation potentials (7.9 Mt CO_2eq yr^{-1}) can be realized with net benefits, compared to livestock (7.7 Mt CO_2eq yr^{-1}) and FOLU (72.3 Mt CO_2eq yr^{-1}) options, which involve net costs, based on use of current technologies. Indeed, if properly implemented, mitigation potentials on cropland can be realized with the additional benefit of 19.41 billion MXN, whereas net costs are incurred for livestock and FOLU options at 14.92 and 23.82 billion MXN, respectively. States for which cropland mitigation potentials are highest are Veracruz, Jalisco and Michoacán and intermediate (between 0.4 to 0.6 Mt CO_2eq) in the states of Chiapas, Sinaloa, Guanajuato, Mexico and Guerrero.

Rapid assessment of mitigation potentials can support discussions in government and among stakeholders about priority actions for reducing emissions. Our data driven and evidence-based results help the government of Mexico refine its national GHG inventory and NDC target as well as monitor progress towards it. This analysis further provides an example of a methodology and results that can help inform future efforts in other countries.

Disclosure statement

The authors report there are no competing interests to declare.

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Data availability statement

The data used in this analysis will be made publicly available *via* a subsequent data paper.

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