ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Financing climate change mitigation in agriculture: assessment of investment cases

To cite this article: Arun Khatri-Chhetri *et al* 2021 *Environ. Res. Lett.* **16** 124044

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
26 September 2021

REVISED
29 October 2021

ACCEPTED FOR PUBLICATION
3 November 2021

PUBLISHED
1 December 2021

LETTER

Financing climate change mitigation in agriculture: assessment of investment cases

Arun Khatri-Chhetri[1,*], Tek B Sapkota[2], Bjoern O Sander[3], Jacobo Arango[4], Katherine M Nelson[3] and Andreas Wilkes[5]

[1] CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), The Alliance of Bioversity International and CIAT, Cali, Colombia
[2] International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico
[3] International Rice Research Institute (IRRI), Hanoi, Vietnam
[4] International Center for Tropical Agriculture (CIAT), Cali, Colombia
[5] UNIQUE forestry and land use, Freiburg, Germany
[*] Author to whom any correspondence should be addressed.

E-mail: arunkhatri0913@gmail.com

Keywords: climate finance, mitigation, agriculture, stakeholders, financial institutions

Abstract

More than one-quarter of the world's greenhouse gas emissions come from agriculture, forestry, and land-use change. As with other sectors of the economy, agriculture should also contribute to meeting countries' emission reduction targets. Transformation of agriculture to low-carbon food systems requires much larger investments in low emission development options from global climate finance, domestic budgets, and the private sector. Innovative financing mechanisms and instruments that integrate climate finance, agriculture development budgets, and private sector investment can improve and increase farmers' and other value chain actors' access to finance while delivering environmental, economic, and social benefits. Investment cases assessed in this study provide rich information to design and implement mitigation options in agriculture through unlocking additional sources of public and private capital, strengthening the links between financial institutions, farmers, and agribusiness, and coordination of actions across multiple stakeholders. These investment cases expand support for existing agricultural best practices, integrate forestry and agricultural actions to avoid land-use change, and support the transition to market-based solutions.

1. Introduction

Food production and consumption are gradually becoming a dominant source of greenhouse gas (GHG) emissions globally. More than one-quarter of the world's GHG emissions come from agriculture, forestry, and land-use change, and this is likely to increase in the absence of mitigation actions in the sector (IPCC 2019, McKinsey 2020). Livestock is a dominant sub-sector in agricultural emissions (31%) followed by crop production (27%) and land-use change (24%) (Poore and Nemeek 2018). Regional disparities in agricultural emissions can also be observed based on production systems, input use, and level of agriculture intensification. Agriculture alone contributes an average of 18% of the net GHG emissions of the large emerging economies (Brazil, Russia, India, China, and South Africa-BRICS). Five countries (China, Brazil, India, United States, and Indonesia) with agricultural emissions of more than 200 Mt CO_2eq contribute about 42% of the total global agriculture emissions (Richards *et al* 2015).

Achieving the global target of limiting 1.5 °C–2.0 °C warming under the Paris Agreement would require large changes in current food production, distribution, and consumption patterns (IPCC 2019, Steiner *et al* 2020). In addition, actions to reduce agricultural GHG emissions can have a synergistic effect on several Sustainable Development Goals (SDGs) (Campbell *et al* 2018). Promotion of low emissions agriculture development directly contributes to Climate Action (SDG 13) as the goal considers both adaptation and mitigation actions. Moreover, the first United Nations Food Systems Summit (2021) also stands in full support of global food systems transformation for more resilient and low emissions agriculture development. These all global initiatives emphasize investments in scaling up innovations that support resilience building and low emissions development in agriculture and allied sectors.

Recent GHG mitigation research in the agriculture and allied sectors has explored a range of options that can significantly reduce GHG emissions from the global food systems. Avoiding land conversion and restoring degraded lands offer large potential GHG emissions reductions and enhance carbon sequestration (Frank *et al* 2017, Griscom *et al* 2021). Advances in agronomy (tillage, nutrient, water, weeds, and energy management) and improved breeding also have a large potential to reduce GHG emissions from crop fields (Beach *et al* 2016, McKinsey 2020). Livestock accounts for up to half of the technical mitigation potential of the agriculture, forestry, and land-use sectors (Herrero *et al* 2016). Mitigation options in the livestock sector include improved feed and manure management, grazing optimization, development of silvopastoral systems, and reduction in demand for livestock products (Hristov *et al* 2013a, Grossi *et al* 2019).

Despite the large GHG mitigation potential, limited actions have been implemented to reduce emissions from agriculture. Implementation of many mitigation actions in agriculture identified in nationally determined contributions (NDCs) of developing countries is conditional on technical and financial supports from the bilateral, multilateral and other financing mechanisms (Pauw *et al* 2020). Even developed countries are relying on a combination of voluntary policies with modest target setting for agriculture (OECD 2019). In addition, the agriculture sector's potential to address climate change is overshadowed by countries' aggregate emission reduction ambition. The mitigation potential of countries providing specific targets for agriculture in their NDCs is about 15% of 2030 business as usual emissions (Richards *et al* 2016), which is far below the technical as well as the economic potential of emissions reduction from agriculture. Similarly, current climate finance for GHG mitigation from agriculture, forestry, land-use, and natural resource management is very limited, amounting to less than 2% of total global mitigation finance (Buchner 2019). Continued lack of progress in agriculture GHG emissions reduction with modest targets and limited finance could constrain efforts to achieve net-zero emissions by 2050 (Gernaat *et al* 2015, Wollenberg *et al* 2016).

Total GHG mitigation investment in agriculture and allied sectors will likely continue to remain smaller than other sectors (e.g. energy and transportation) for the foreseeable future. Implementation of mitigation actions identified in NDCs and other commitments requires an increase in investment shares over the next decades. One of the reasons for slow progress in GHG emissions reduction in agriculture could be the lack of business cases that can provide a strong basis for public and private investment in mitigation actions. Impact investments can shift public spending and private finance to low-carbon agriculture and support implementing NDCs. The opportunities to mobilize investments in agriculture emissions reduction presented by the Paris Agreement and NDCs are mostly unrealized. One of the main reasons is the lack of a pipeline of business cases to make investment in agricultural GHG mitigation options (Sadler 2016). However, the possibilities for mitigation finance in agriculture include a range of activities in food systems (OECD 2019). Investments for agriculture emissions reduction need to move beyond traditional loans and technical assistance approaches by developing innovative financing mechanisms that can leverage private investments in mitigation actions (WBCSD 2020, USFRA 2021). Little experience and information are currently available about how mitigation investments best support the long-term and widespread adoption of low emission technologies and practices in agriculture and allied sectors.

This study assessed investment cases that link field evidence of economic relevance and potential to reduce agricultural GHG emissions by reaching the scale. This paper presents (a) an evaluation of investment cases that hold promise for reducing GHG emissions from the agriculture sector and support mitigation policies, and (b) discusses innovative approaches applied to overcome current barriers in financing in low emissions development agriculture. The assessment focuses on innovative financial mechanisms and instruments that can improve and increase farmers' access to finance and deliver environmental, economic, and social benefits. This study considers five different investment cases in four regions (Southeast Asia-Thailand and Vietnam, South Asia-India, Africa-Kenya, and Latin America-Colombia) and explores possibilities of climate finance for mitigation actions in agriculture and allied sectors in the different agro-ecologies. Investment cases include three major agriculture sub-sectors—paddy rice cultivation, crop nutrient management, and livestock.

2. Methods

2.1. Selection of investment cases

This assessment selected five investment cases: (a) Thai Rice NAMA (Nationally Appropriate Mitigation Action), (b) climate-smart rice production in Vietnam, (c) soil health card (SHC) scheme for crop nutrient management in India, (d) Dairy NAMA in Kenya, and (e) Livestock NAMA in Colombia. This study considered the following four criteria to select the investment cases: (a) it must represent GHG mitigation in the agriculture sector, (b) includes different agriculture-sub sectors that have a large

Table 1. Mitigation options in the investment case and their potential impacts.

Mitigation options	Investment case	Potential impact
Alternate wetting and drying (AWD)	Thai Rice NAMA, climate-smart rice production in Vietnam	Decrease water consumption by ∼30%, reduced production cost without yield loss, and reduced GHG emissions (CH_4) by 30%–70% (Richards and Sander 2014, Allen and Sander 2019).
Mid-season drainage	Climate-smart rice production in Vietnam	Decrease CH_4 emission by ∼52% (Liu *et al* 2019)
Site-specific nutrient management	Thai Rice NAMA, SHC scheme in India	Reduced fertilizer (in excess fertilizer use locations), possibly increased yield with balanced fertilizer use, and reduce GHG emissions with an increase in nutrient use efficiency (Buresh *et al* 2019, Sapkota *et al* 2021).
Straw management	Thai Rice NAMA, climate-smart rice production in Vietnam	Removing rice straw in the flooded field and avoiding burning reduces a large amount of emissions from rice cultivation (Allen 2020).
Laser land leveling	Thai Rice NAMA	Increased water and nutrient use efficiency in rice fields, increase yield and income (Aryal *et al* 2015). Decreased emissions by decreasing amount of water and fertilizer use, and facilitation of AWD practice (Gill 2014).
Improved feed with fodder production	Dairy NAMA in Kenya, Livestock NAMA in Colombia	Improving forages and feed quality for cattle reduces methane emissions (Hristov *et al* 2013b, Herrero *et al* 2016).
Dairy plant retrofit- energy saving in milk collection, cooling, and processing facilities	Dairy NAMA in Kenya	Dairy plant retrofit offers significant GHG emissions reduction with decreased costs of production, milk losses, and water consumption (Wilkes *et al* 2018).
Manure management with biogas plants	Dairy NAMA in Kenya, Livestock NAMA in Colombia	Anaerobic digestion of manure with biogas plants can reduce GHG emissions and reduce energy costs to livestock farmers (Lyng *et al* 2018).
Restore grazing land through silvopastoral livestock systems	Livestock NAMA in Colombia	Improved soil carbon stock (Herrero *et al* 2016) and reduces GHG emissions from livestock (Thornton and Herrero 2010).

potential to reduce GHG emissions in the region, (c) includes multiple financing sources and instruments, and (d) have linkage to the countries' NDCs submitted under the United Nations Framework Convention on Climate Change (UNFCCC). The authors of this study contributed to generate scientific evidence of many mitigation options considered in the NAMAs (table 1) through the CGIAR research program on climate change, agriculture, and food security (CCAFS). In some cases, authors participated in the stakeholders' consultations events organized by the NAMA preparation teams. However, the authors of this paper were not responsible for the final development of any investment cases considered for this study. Colombia, Kenya, and Thailand developed sub-sector NAMAs with detailed mitigation actions and allocation of finance. These NAMAs consider technologies and practices for scaling and investment that have been tested and evaluated in the field (table 1).

Colombia's NAMA proposal includes mitigation options for the livestock (cattle) sector. Restoration of grazing land through silvopastoral systems, manure management, large-scale plantation of forage trees, and avoiding deforestation are key components of Colombia's NAMA for sustainable livestock production (Palmer 2015). Kenya developed a NAMA for its dairy sector to scale up mitigation actions and reach more than 0.6 million dairy farmers (MALF 2017b). This NAMA targets increasing on-farm dairy productivity, reducing high-emissions energy use, and strengthening institutional and farmers' capacities for scaling up low-emission dairy development. The Thai Rice NAMA aims to transform rice production by replacing current practices with more sustainable and less methane-emitting approaches (NAMA Facility 2020). This shift towards low-emissions rice production comprised three key components: technical assistance and training on implementation of new rice cultivation technologies and practices, policy formulation and supporting measures, and investment.

Vietnam has raised the agriculture GHG emissions reduction target in its updated NDCs (GoV 2020). Climate-smart rice production can significantly contribute to achieving the mitigation target in Vietnam. The Sustainable Agriculture Transformation project in Vietnam is promoting AWD and rice straw management to enhance rice productivity and emission reduction. GHG mitigation from the agriculture sector is not a priority for India, but its NDC includes a scheme for SHC among its adaptation strategies (GoI 2016). The goal of this scheme is to improve crop-wise nutrient management for individual farms and help farmers to improve crop productivity and reduce the amount of fertilizer applied. Studies indicate that India has the highest excess nitrogen balance in crop fields (Tesfaye *et al* 2021) and the country can reduce a large amount of GHG emissions with the use of soil health information-based precision nutrient management (Sapkota *et al* 2021).

2.2. Analysis of investment cases

2.2.1. Sustainability indicators of investment

This study evaluates the selected investment cases in relation to selected sustainability indicators. We considered environmental, economic, and social indicators of mitigation options to evaluate the mitigation options in the investment cases. Environmental indicators include reduction of net GHG emissions (emissions and removals), input use efficiency (i.e. nutrient, water, and energy), and ecosystem services (i.e. improving soil health, water quality, and air pollution). These environmental indicators for agricultural practices and technologies have been evaluated by multiple studies (Aryal *et al* 2015, Kashangaki and Ericksen 2018, Wilkes *et al* 2018, Sander *et al* 2020, Sapkota *et al* 2021). Some of the indicators, such as improving soil health and long-term preservation of soil carbon, are critical for agricultural productivity and GHG emission reduction (Dickie *et al* 2014). These interventions increase synergies between mitigation in SDG 13 with efficiencies in water, nutrient, and energy inputs in food production.

Economic indicators of sustainability include changes in production and income from the implementation of mitigation options. These indicators offer a strong motivation to farmers and ranchers to implement the mitigation options in their crop and pasture lands, and dairy plants retrofit by dairy companies (Vermeulen *et al* 2016, Khatri-Chhetri *et al* 2020b). Contribution to food production and income largely covers processes towards achieving no poverty (SDG 1), zero hunger (SDG 2), and responsible consumption and production (SDG 12). The broader food systems transformation goal integrates both environmental and economic indicators (Campbell *et al* 2018, Steiner *et al* 2020). Gender relationships in agriculture production systems can influence the way mitigation options are prioritized, transferred, and adopted (Edmunds *et al* 2013). The roles and interests may vary for women and men in agriculture, which can lead to different impacts as measured by different sustainability indicators. GHG mitigation options for agriculture must not increase women's drudgery who are already overburdened from agricultural and household activities (Khatri-Chhetri *et al* 2020a). In many locations, women play a large role in managing irrigation, fertilizer application, manure and crop residue management, livestock feeding, and maintenance of agroforestry systems (Gartaula *et al* 2020, Wilkes *et al* 2020a).

We evaluated sustainability indicators of the selected mitigation options based on the already published literature. Authors assigned the score 3–0 based on their level of impact on each indicators: 3 = high impact, 2 = medium impact, 1 = low impact, 0 = literature did not evaluate the selected mitigation option for that indicator. This scoring method is consistent with the other studies that evaluated sustainability indicators of climate change adaptation and mitigation options in agriculture and allied sectors (Thornton *et al* 2018, van Wijk *et al* 2020).

2.2.2. Investment impact

This study assessed the planned/proposed investments in the selected cases and their potential impact on GHG reduction from the agriculture sub-sectors. Investment cases for Thailand and Vietnam focus on emission reduction from paddy rice cultivation. Paddy rice cultivation contributes 55% (27.86 Mt CO_2eq) and 48% (42.56 Mt CO_2eq) of the total agriculture emissions in Thailand and Vietnam, respectively (GoV 2017, MNRE 2018). This study presents the mitigation potential of the selected options in the Thai Rice NAMA and climate-smart rice production in Vietnam based on previous estimates and compares them with emission reduction targets set by investment cases.

Improving nutrient use efficiency in crop fields is the main objective of the SHC program in India. This program is included in the country's adaptation strategies with a commitment to enhancing investment in climate-vulnerable sectors. Synthetic fertilizer use in crop production is one of the major sources of agricultural emissions in India. There is significant potential to reduce fertilizer-induced GHG emissions from increased N use efficiency and by switching to alternative sources of crop nutrients (Trirado *et al* 2010). Although India has no target for agricultural emission reduction in its NDC and other domestic policies, it could reduce its GHG emissions from agriculture by almost 18% through the adoption of efficient use of fertilizer, tillage, and water management practices (Sapkota *et al* 2019). Intensive crop production systems in India have a large excess nitrogen balance in crop fields (Tesfaye *et al* 2021). This study estimates the impact of the SHC program on GHG reduction in India.

The investment cases in Kenya and Colombia consider livestock and pasture land management. Kenya's NAMA focuses on the dairy sector which is responsible for about 12.3 Mt CO_2eq yr^{-1} emission (FAO and NZAGRC 2017). The use of a combination of feed practices, dairy plant retrofit, and manure management has a large GHG mitigation potential in Kenya. The livestock sector in Colombia also contributes about 26% of the country's total GHG emissions (IDEAM *et al* 2016). Cattle farming alone is producing 95% of the livestock sector's emissions. This cattle farming is dependent on the management of more than 34 million ha of pasture land across the country. Colombia is targeting to reduce 13.46 m $tCO_2eq\ yr^{-1}$ emission from the agricultural sector (Tapasco *et al* 2019). This study assesses the Kenya and Colombia NAMAs and their contribution to achieving the NDC targets.

2.2.3. Mapping sources of finance

Diversification and catalytic investments for climate actions in agriculture are critical to realizing the GHG mitigation goals and de-risking investment in agriculture programs. This study assesses the types and sources of finance in the selected investment cases. De-risking investment in climate actions enhances public–private partnerships (PPPs) to leverage the financial and technical capacities of different stakeholders and attract additional capital diversifying the risk-return profiles of individual investors (Sadler 2016, Guarnaschelli *et al* 2018). This also requires building a wide range of financial instruments that can link investors to smallholders and agricultural small and medium enterprises (SMEs). All investment cases were assessed based on their role in (a) developing and improving the mitigation finance environment for agriculture, (b) supporting diversification of finance sources and instruments to implement the mitigation options, and (c) enhancing PPPs.

3. Results

3.1. Sustainability indicators of investment cases

Mitigation options selected by the investment cases have significant GHG emissions reduction and/or carbon sequestration potential in agriculture and allied sectors (table 2). Many researchers in the CGIAR research program on CCAFS have previously evaluated AWD, residue management, laser land leveling, and site-specific nutrient management in agriculture systems, particularly in paddy rice cultivation in India, Thailand, and Vietnam. Studies show that proper use of these agriculture practices can reduce net GHG emissions by increasing input use efficiency and improving soil and water management. The AWD practice significantly reduces GHG emissions by an average of 45% (IPCC 2019). Depending on baseline conditions, this could range from 1 to 5 $tCO_2eq\ ha^{-1}\ season^{-1}$ compared to continuous flooding practice (Vo *et al* 2020). Co-benefits of AWD include lower use of water, fertilizer and seed, and higher resistance to some pests, diseases, and lodging damage (Farnworth *et al* 2017, Allen and Sander 2019).

Straw burning or incorporation in fields are common practices in the paddy rice-growing areas. Studies show that in flooded paddy rice, straw incorporation usually stimulates CH_4 production (Jiang *et al* 2019). However, incorporation of paddy straw into the soil under non-flooded conditions more than 30 d before the next rice season has the potential to increase soil organic carbon and reduce CH_4 emissions during the paddy rice season compared to incorporating the straw in flooded conditions within a short duration (<30 d) before the rice planting season (Sharma *et al* 2019). Studies also show that a combination of tillage, water, fertilizer, and residue management in paddy rice fields generates large mitigation benefits as well as improvement in productivity and input use efficiency (Sapkota *et al* 2015, Richards *et al* 2019). An evaluation of site-specific nutrient management practice in India observed increased rice yield and reduced fertilizer consumption and associated GHG emissions from the rice fields (Sapkota *et al* 2021). These practices also contribute to economic indicators by increasing farm production and/or income. The change in net income is associated with an increase in crop productivity or decrease in input use by improving input use efficiency.

Evaluations of improved feed with fodder production, grazing land management, dairy plant retrofit, and manure management show a large GHG mitigation potential from the livestock sector including economic and social benefits in Kenya and Colombia. The GHG emissions reduction potential of the use of different types of fodder across Kenya ranges from 0.6 to 3.0 Mt $CO_2eq\ yr^{-1}$ (FAO and NZAGRC 2017). Increased feeding of higher quality roughages, such as leguminous fodder, hay, silage, and crop byproducts, as part of balanced feeding programs, can reduce farmers' reliance on concentrate feed, which has a relatively high carbon footprint (Garg *et al* 2016). Similarly, the implementation of silvopastoral systems in Colombia can reduce GHG emissions by 2.6 $tCO_2eq\ ha^{-1}\ yr^{-1}$ compared to the current practices, while increasing agricultural productivity and income (Landholm *et al* 2019). Other research also suggests that promoting balanced feed rations could provide important opportunities to increase milk production and reduce emission intensity (Wilkes *et al* 2020b).

Dairy processing plants use a large amount of energy, mainly electricity and fossil fuels, for cooling and storage, pasteurization, evaporation, and drying activities. Improvement in energy use efficiency in the major dairy processing plants in Kenya can reduce emissions by 0.14 Mt $CO_2eq\ yr^{-1}$ including a large cost saving (Wilkes *et al* 2018). Most milk losses in the dairy sector in Kenya occur at the production and processing stages, as milk is transported from farmer to cooperative and to local processors. The estimated GHG emission reductions from minimizing the loss in milk cooling centers and dairy cooperatives in Kenya were 1.7 and 1.2 Mt $CO_2eq\ yr^{-1}$, respectively (Gromko and Abdurasulova 2018). Some selected mitigation options in the investment cases such as site-specific nutrient management, fodder production, restoring grazing lands, and manure management provide co-benefit of ecosystem services.

Table 2. Sustainability indicators of the selected mitigation options in the investment cases.

Mitigation options in the investment cases	GHG emissions	Input use efficiency	Ecosystem services			Production	Income	Gender	References
			Soil health	Water quality	Air pollution				
Laser land leveling	Medium	High	Not evaluated	Not evaluated	Not evaluated	Low	Medium	Not evaluated	Aryal *et al* (2015)
Alternate wetting and drying (AWD)	High	Medium	Low	Low	Low	Medium	Medium	Low	Thu *et al* (2016), Chidthaisong *et al* (2018), Tran *et al* (2018)
Site-specific nutrient management	Medium	High	Medium	Medium	Low	Medium	Medium	Not evaluated	Kantachote *et al* (2016), Trinh *et al* (2017), Sapkota *et al* (2021)
Straw management	High	Not evaluated	Medium	Low	Medium	Not evaluated	Low	Low	Vu *et al* (2015), Tariq *et al* (2017)
Improved feed with fodder production	High	Medium	Medium	Low	Not evaluated	Medium	Medium	Low	FAO (2017), Kashangaki and Ericksen (2018)
Dairy plant retrofit	High	Medium	Not evaluated	Not evaluated	Low	Not evaluated	Medium	Not evaluated	Wilkes *et al* (2018)
Manure management with biogas plants	High	Medium	Medium	Medium	Medium	Medium	Medium	Low	Hamid and Blanchard (2018)
Restore grazing land through silvopastoral livestock systems	High	Low	Medium	Medium	Not evaluated	Medium	Medium	Low	Landholm *et al* (2019), Aynekulu *et al* (2020)
Link to the Sustainable Development Goals	SDG 13	SDG 13	SDG 6, 13	SDG 6, 14	SDG 3	SDG 1, 2	SDG 1, 2	SDG 5	
Level of impact	High		Medium		Low		Not evaluated		

Note: high represents a major impact on sustainability indicators, and medium and low are additional impacts. SDG 1(no poverty), SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (gender equality), SDG 6 (clean water and sanitation), SDG 13 (climate action), and SDG 14 (life blow water).

Table 3. Projected impact of investment cases.

Investment case	Investment	Scaling target	GHG mitigation
Rice NAMA in Thailand	US$ 92.6 M over 5 years	• 100 000 farmers and support to 420 service providers	• 1.66 Mt CO_2eq over 5 years • Reduce baseline emissions from irrigated rice by >26%
Dairy sector NAMA in Kenya	US$ 223 M over 10 years	• 153 000 dairy farming households • 151 dairy processing facilities • 20 000 household biogas plants	• 8.08 Mt CO_2eq over 10 years • Increase dairy productivity: 4.14 Mt CO_2eq • Energy efficiency in processing: 2.96 Mt CO_2eq • Biogas plant adoption: 0.98 Mt CO_2eq
Livestock NAMA in Colombia	US$ 1100 M over 10 years	• Restore 1.6 M ha of grazing lands • Plant over 2 Mha with improved, nutritious forage plants • Benefit around 200 000 farming families	• Reduce 4 Mt CO_2eq by enteric fermentation • Capture 6 Mt CO_2eq by Silvi-pastoral system • Capture up to 167 Mt CO_2eq by restored ecosystems • Avoid deforestation of 2.5 Mha of forest, mitigating 1228 Mt CO_2eq
Soil health card in India	US$ 107.51 M over 5 years	140 M farmers	• Reduction in chemical fertilizer use by 8%–10% equivalent[a] to 7.34–9.18 Mt CO_2eq at the current level N fertilizer use (17.63 Mt) • 17.52 Mt CO_2eq yr^{-1} through efficient fertilizer management[b]
Climate-smart rice production in Vietnam (NDCs)	Integrated with agriculture extension budget	1.2 Mha rice fields by 2030	• 4.14 Mt CO_2eq annual reduction by 2030 • Adoption of AWD on 0.2 M ha and mid-season drainage on 1 Mha rice fields by 2030 contributing 65% of the agriculture sector's annual mitigation potential with domestic contributions.

[a] A study conducted by the National Productivity Council stated that the application of SHC recommendations has led to a decline of 8%–10% in the use of chemical fertilizers (MAFW 2021).
[b] Better nutrient management technologies in Indian agriculture has the potential to reduce 17.5 Mt CO_2eq yr^{-1} (Sapkota *et al* 2019).

They help to minimize nutrient run-off from the agriculture and pasture lands, improve water quality and soil health, and reduce air pollution.

Given the existing gender inequalities in agriculture, the outcomes of mitigation investment might not be equally beneficial to women and men. In smallholder households across Kenya and Colombia, women play a predominant role in cattle feeding, milking, cleaning, and, to some extent, delivery of milk to the market and milk collection centers (Kristjanson *et al* 2014, Gallina 2016). Men tend to have a larger role in activities related to animal health, such as artificial insemination, seeking veterinary treatment, and the sale of live animals and animal products. Investment in improved feed with fodder production, manure management and restoring grazing land through silvopastoral livestock system can reduce women's drudgery in livestock production. But overall gender impact of mitigation options depends on women and men's roles not only in agriculture production but also in decision-making over input supply and marketing (Wilkes *et al* 2020a).

3.2. Investment impacts

The amount of investment in the selected cases ranged from US$ 68 million over 5 years to US$ 1100 million over 10 years. All investment cases target reaching a certain number of farmers and/or areas under the mitigation options, SMEs, and/or dairy processing facilities (table 3). Thailand's NAMA Support Project (NSP) targets reaching 100 000 farmers and supports 420 service providers. The project provides capacity-building training to the farmers on how to implement mitigation technologies and sustainable best practices in paddy rice production. This investment also supports the implementation of a new voluntary standard to verify rice sustainability, including farmers' safety, labor rights, and the application of low-emissions practices. The project envisioned to boost farmers' income by applying appropriate technologies and effective inputs management for paddy rice production (saving water, energy, fertilizer, and pesticides, etc) and facilitating the sale of low-emissions rice. The NSP anticipates reducing baseline emissions by more than 26% from irrigated rice fields, which is about 1.66 Mt CO_2eq over 5 years.

The low-emission and climate-resilient dairy development proposal aims to transform Kenya's dairy sector by improving on-farm dairy productivity, reducing high-emission energy use, and strengthening the capacities of national institutions and stakeholders for upscaling good dairy management practices. The project targets 153 000 dairy farming households and 151 dairy processing facilities and aims to support 20 000 households to adopt biogas over 10 years. The project plan to cover about 17% of the total population of dairy farmers in Kenya with 50% women beneficiaries and generate 12 000 new jobs in the dairy processing sector. Over the 10 years implementation period, the estimated total emission reduction is 8.08 Mt CO_2eq from increased dairy productivity (4.14 Mt CO_2eq), energy efficiency in dairy processing facilities (2.96 Mt CO_2eq), and household biogas adoption (0.98 Mt CO_2eq).

The livestock NAMA proposal from the Colombian government targets to save a large amount of GHG emissions (more than a billion tCO_2eq), while protecting forests, regenerating pasture and degraded lands, and boosting income from the livestock sector. The program aims to reduce 4 Mt CO_2eq by enteric fermentation, capture 6 Mt CO_2eq by the silvopastoral system, and up to 167 Mt CO_2eq by restored ecosystems, and mitigate 1228 Mt CO_2eq from the avoided deforestation of 2.5 M ha of forest in the country. These emissions reduction and carbon sequestration target to restore a total of 1.6 M ha of grazing land through intensive and non-intensive silvopastoral livestock systems, and plant over 2 million ha with improved and nutritious forage trees in the degraded pasture and other lands.

The increasing amount of chemical fertilizer consumption with low fertilizer use efficiency (<50%) is one of the major concerns for sustainable agriculture development in India (Fishman *et al* 2016). The imbalanced application of different types of chemical fertilizer remains a widespread problem in many locations in the country. The government is also facing the rising cost of fertilizer subsidies, and this subsidy leading to excess nutrient application, largely nitrogen fertilizer, in many crops. The government of India has launched the SHC program in 2015 to provide fertilizer use recommendations to the farmers based on nutrient availability in their soils. The initial estimated investment for the program was US$ 85 million to reach 140 million farmers across the country. The program used US$ 107.5 million from 2015 to 2020 to develop soil testing infrastructure, soil sample collection, and testing, and distribution of SHCs to over 150 million farmers throughout India (MAFW 2020). This program established 9285 new Soil Testing Labs and promoted village-level soil testing facilities run by agri-entrepreneurs. Studies indicate that soil health schemes in India promoted sustainable farming leading to a decrease of chemical fertilizer use by 8%–10% and an average increase in crop yield by 5% (MAFW 2020). This reduction of fertilizer use is equivalent to 7.34–9.18 Mt CO_2eq at the current level of N fertilizer use (17.63 Mt). Another estimate indicates that India can reduce 17.52 Mt CO_2 yr^{-1} through efficient fertilizer management in the crops across the country (Sapkota *et al* 2021).

National Agriculture Extension Center (NAEC) under the Ministry of Agriculture and Rural Development (MARD) of Vietnam is promoting climate-smart rice production across the country to minimize the cost of cultivation, enhance productivity and reduce GHG emissions from paddy rice cultivation. The Government of Vietnam plans to convert 1.2 million ha of conventional paddy rice cultivation to climate-smart production by 2030 using only domestic resources (MONRE 2015). This program promotes changes in rice varieties, soil/water management practices, crop establishment methods, residue management, and reducing post-harvest losses. Vietnam's updated NDC (2020) has raised the agriculture-GHG mitigation target by 16 m tCO_2eq, which will be mainly achieved through emission reduction in rice cultivation. The climate-smart rice cultivation efforts target to promote AWD on 0.2 million ha and mid-season drainage on to 1 million ha rice fields by 2030 contributing 65% of the agriculture sector's annual mitigation potential. Straw and fertilizer management can further reduce the GHG emission from the paddy rice fields.

3.3. Sources of finance and instruments

The Thai Rice NAMA is a joint project funded by NAMA Facility and the Thai Government to encourage smallholder farmers to implement low emissions technologies and practices in paddy rice cultivation. The NSP works with farmers, farmers' associations, and external service providers to develop incentive schemes and financial support. The NAMA Facility approved US$ 17.3 million for this project and Thai Governments committed to leverage an additional US$ 27.7 million per year to the project (table 4). The NSP expects to generate an additional US$ 23.8 million direct financial investment from the private sector. The funding from the NAMA facility is provided through the subsidized loans program implemented by the Bank for Agriculture and Agricultural Cooperatives (BAAC). The funding from the Thai Government covers the costs of agriculture extension services to promote the adoption of low-emissions paddy rice

Table 4. Funding sources and financing instruments in the investment cases.

Investment case	Funding sources	Financing instruments
Thai Rice NAMA	NAMA facility \$17.3 M	Subsidized loans program implemented by the BAAC
	Thai Government \$27.7 M yr^{-1}	Agriculture extension program
	Private sector \$23.8 M	Innovative financial incentives
Dairy sector NAMA in Kenya	Green Climate Fund \$56.1 M	Loan (\$39.19 M), Guarantees (\$10 M), Grants and TA (\$9.77 M)
	Government of Kenya \$2.23 M	Staff cost (\$2.23 M)
	Multilateral donor \$14.58 M	Grants and TA (\$11.75 M), Staff cost (\$1.1 M), other (\$1.28 M)
	Financial institutions \$107.76 M	Loans (\$107.76 M)
	Dairy private sector \$41.97 M	Loans (\$24.71 M), Grants and TA (\$17.26 M)
Livestock NAMA in Colombia	Estimated cost US\$ 1100 M for 10 years (proposal), Prioritized investment: US\$ 925 M; Implementation: US\$ 147 M; Knowledge management: US\$ 13 M; MRV system: US\$ 15 M.	Seeking international partners and financial supports
Soil health card in India	Government of India \$107 M	Establishment of soil testing labs (static and mobile), funding to soil testing facilities developed by agri-entrepreneurs
Climate-smart rice production in Vietnam	MARD, Vietnam	Training and capacity building on climate-smart rice production Support business development by leveraging a national green credit program for capital investment.

cultivation technologies and practices and technical support to implement the NAMA Support Program.

Reaching millions of smallholder dairy farmers in rural areas with financial support is one of the major challenges in Kenya. The State Department of Livestock aims to catalyze investments of US\$ 223 million in Kenya's dairy sector from various sources of finance. The project proposes financial contributions from various sources, such as the Green Climate Fund (25%), commercial financial institutions (48%), the dairy private sector (19%), a multilateral donor partner (6.5%), and the Government of Kenya (1%). This is a unique example of how different financial sources can be combined to support climate change mitigation with agricultural development objectives. This investment case plans to use a loan from the Green Climate Fund to leverage private investment from financial institutions, dairy plants, and farmers in the implementation of mitigation actions in the dairy sector.

Kenya's NAMA investment case uses a variety of financing instruments for the provision of finance to dairy sector stakeholders. The program supports commercial banks and microcredit institutions to provide affordable loans to dairy cooperatives and farmers, including support with capacity building on financial management. Commercial fodder and hay producers can receive financial assistance (concessional loans) for investments in commercial hay production and marketing. Dairy cooperatives and processing plants can also access concessional loans to leverage credit finance from commercial banks for clean energy technologies. Farmers can pursue blended grants and loan finance to overcome the high initial costs of installing biogas digesters at the household level. The funding also leverages investment by private sector dairy processors in dairy extension services to promote the adoption of climate-resilient and low-emissions dairy management practices, with the Government of Kenya and a donor partner financing coordination and management of the program.

The Colombian Government is seeking international partners and financial support to implement livestock NAMA. The estimated cost of this project is US\$ 1100 million, including prioritized investments: US\$ 926 M; implementation: US\$ 147 M; knowledge management: US\$ 13 M; MRV system: US\$ 15 M. The MARD of Colombia (*Ministerio de Agricultura y Desarrollo Rural de Colombia*) is in charge to develop this proposal and coordinating with potential funding partners and developing financing instruments. This livestock NAMA has a direct relation with Colombia's Coffee NAMA that aims to establish an agroforestry system, and with Forestry NAMA that seeks to restore degraded land and reforestation.

The SHC scheme in India is entirely funded by the Government of India. The cost of interventions under the scheme is shared between the central and the state governments (75:25 ratio). This scheme allocates a large amount of funds to renovate and improve existing soil testing facilities and the establishment of new soil testing labs (static, mobile, and mini-labs) through the existing agriculture extension program. Staff from the State Department of Agriculture and Agriculture Universities involve to implement the scheme. Investment in soil testing labs is also done by private companies under the private-public partnership model with subsidy funding from the government. This scheme promotes private agri-entrepreneurs for building village-level soil testing facilities for timely distribution of high-quality soil test results to the small and marginal farmers.

Climate-smart rice production in Vietnam is promoted by the NAEC with funding from MARD. This is entirely a public investment model in which Government's agriculture development fund is allocated to develop training materials on climate-smart rice production for extension staff and rice farmers. The MARD coordinates to bring the experts from the various agencies to develop training modules and provide training to the agriculture extension staff. This program also supports private sector business development by leveraging a national green credit program for capital investment to provide mitigation technology services to paddy rice farmers. An additional 27% (25.8 Mt CO_2eq) reduction in agricultural emissions has been designated for international (conditional) funding. The internationally funded NDC actions in rice include converting an additional 1.5 million ha to AWD and 1 million ha to integrated crop management (ICM) which is expected to reduce annual emissions by 9.86 Mt CO_2eq by 2030.

4. Discussion

4.1. Science—investment nexus

Five investment cases considered in this study have a strong scientific base to invest in GHG mitigation impacts. The Thai Rice NAMA and climate-smart rice production in Vietnam used scientific evidence generated from a long research collaboration between government agriculture departments, International Rice Research Institute (IRRI), and other national and international research organizations. This collaboration evaluated low emission paddy rice production technologies (i.e. AWD, mid-season drainage, laser land leveling, straw management, and site-specific nutrient management) in different locations of Philippines, Thailand, and Vietnam (Vu *et al* 2015, Kantachote *et al* 2016, Thu *et al* 2016, Tariq *et al* 2017, Trinh *et al* 2017, Chidthaisong *et al* 2018, Tran *et al* 2018). A consortium composed of the Thai Rice Department, The Deutsche Gesellschaft für Internationale Zusammenarbeit, IRRI, and other rice-based public/private partners developed the NAMA proposal integrating field evidence of mitigation technologies and practices. IRRI has contributed estimation of the mitigation potential from the implementation of climate-smart rice cultivation practices. A suitability mapping for AWD and an investment plan for low-emission rice production developed by IRRI and CCAFS in collaboration with national partners also contribute to the design planning and implementation of the climate-smart rice production program in Vietnam to meet the agricultural NDC targets (Nelson *et al* 2015, Tran *et al* 2019).

Imbalance use of crop nutrients, excess application of nitrogen fertilizer in many places, and low nutrient use efficiency are major concerns for sustainable agriculture production in India. Studies indicate that the increasing environmental loss of nitrogen is enhancing GHG emissions from the crop fields (Moring *et al* 2021, Sapkota *et al* 2021). The annual fertilizer consumption, particularly fertilizer nitrogen, has been continuously increasing in India requiring more and more government subsidies in fertilizer. The nutrient use efficiency of cropping systems in India (expressed in yield per unit of nitrogen input) decreased from 55% in 1960 to 35% in 2010 (Singh 2017). The SHC scheme in India was introduced in 2015 to promote the balanced use of crop nutrients based on nutrients available in the soil and improvement in nutrient use efficiency. Under this scheme, 93 million SHCs based on test results of 23.6 million soil samples and area-general fertilizer recommendations have already been distributed to farmers (Kishore *et al* 2021). However, preparing a meaningful fertilizer recommendation ahead of each planting season for such a large number of SHC holders with limited soil testing facilities and capacity is a major challenge for the government of India. The government extension system should focus on adequately educating farmers on what soil test data mean and how to use these in terms of meeting the nutrient requirement of crops through the adoption of various precision nutrient management strategies. Many recent studies in India also provide ample scientific evidence of increasing nutrient use efficiency by the application of balanced nutrients combined with tillage and water management practices (Buresh *et al* 2019, Jat *et al* 2019, Sapkota *et al* 2021).

Kenya's Dairy NAMA proposal intends to implement low-emission, climate-resilient, and productivity-enhancing options in the dairy sector. This is reinforced by the scientific evidence of mitigation potential and economic viability. Recent studies estimate GHG emission reduction potential from livestock feed management and breed improvement (FAO and NZAGRC 2017), retrofitting dairy processing plants (Wilkes *et al* 2018), installing biogas plants for manure management (MALF 2017b), and reducing milk loss and waste (Gromko and Abdurasalova 2018) in Kenya. CCAFS worked with the State Department for Livestock and national stakeholders to develop the NAMA proposal, and national agencies further supported the integration of the proposed actions in Kenya's national climate change action plan and NDC (Government of Kenya 2020). It is hoped that explicit integration of the Dairy NAMA in

Table 5. Agriculture emission reduction target in NDCs.

Country	Agriculture mitigation in NDC	Emission reduction target in agriculture
Colombia	Agroforestry and reduction in deforestation	No emissions reduction target in agriculture but it targets to reduce50% of total GHG emissions from a business-as-usual scenario by 2030.
India	Forest management and afforestation (Agriculture Soil Health Management is included as an adaptation strategy)	Economy-wise, no emissions reduction target in agriculture
Kenya	Climate-smart agriculture with emphasis on an efficient livestock management system	Economy-wise, emission reduction target by 32% compared to 2030 BAU emissions.
Thailand	Economy-wise excluding land use, land-use change, and forestry	Economy-wise targets to reduce 20% of total GHG emissions from a business-as-usual scenario by 2030.
Vietnam	Rice cultivation, rumen digestion, improved crop management, and fertilizer management	Domestic resources: 6.8 Mt CO_2eq yr^{-1} (6% of BAU scenario) by 2030 International support: 25.8 Mt CO_2eq yr^{-1} (23% of BAU scenario) by 2030.

national policies can strengthen the country's ability to attract international investment.

The NAMA for livestock was informed by scientific evidence of low emission livestock development in Colombia. Studies show that the use of improved feed in a combination of fodder and grasses can reduce enteric methane emissions from cattle in Colombia (Ruden *et al* 2018, Arango *et al* 2020). Colombia's livestock federation also uses these results to strengthen its sustainable livestock strategy and improve pasture lands. Reducing deforestation and the implementation of silvopastoral systems have large emission reduction potential while increasing livestock productivity and restoration of degraded landscapes (Landholm *et al* 2019). The Climate-smart agriculture profile of Colombia indicates that agroforestry, silvopastoral systems, and grassland management are the key interventions for climate change adaptation, mitigation, and productivity benefits for livestock farmers in Colombia (World Bank, CIAT, CATIE 2014). Recommendations of these scientific studies were incorporated to design the mitigation strategies in the livestock NAMA.

4.2. Return on investments for private sector

The five investment cases integrate multiple financial sources and instruments that offer a return for investors in various forms. Governments are the main source of finance in all cases that leverage funds to support farmers' capacity strengthening and business development opportunities for private sector service providers in agriculture. The return on investment for government finance includes social welfare and economic growth that is difficult to account in a balance sheet. Financial institutions and the private sectors are the key investors in Thai Rice NAMA and the Dairy sector NAMA in Kenya. In Thailand, the private sector invests to provide mitigation technology services to farmers such as laser land leveling, AWD, site-specific nutrient management, and straw/stubble management on a large scale, and in turn, generate revenue. Business case assessments of these mitigation options also indicate promising opportunities for private sector investment (Tran *et al* 2019, World Bank 2019).

In Kenya, financial institutions and private dairy plants invest in three commercially viable projects—information services, fodder supply, and dairy plant retrofit. Farmers, dairy cooperatives, and dairy processing plants are the key user of loan money in the dairy NAMA project. Studies also indicate that fodder supply and dairy plant retrofit are business cases viable for private sector investment in Kenya (Dijk *et al* 2018, Gromko and Abdurasalova 2018, Kashangaki and Ericksen 2018, Wilkes *et al* 2018). Investment in soil health testing mini and micro laboratories is an economically viable investment in India. Private investors charge fees in return for service provision. These examples set cases for impact investing to make investments in commercial projects, companies, or farmers that create sustainable impact and offer a return for investors.

4.3. Alignment between mitigation target and potential

Only Vietnam has an explicit agricultural sector emission reduction target in its NDC. Colombia, Kenya, and Thailand include economy-wide targets to reduce total GHG emissions in their NDCs (table 5). Agriculture mitigation in Kenya's NDC aims to scale-out climate-smart agriculture with emphasis on an efficient livestock management system including feed, breed, and value chain of livestock products (MoEF 2020). The promotion of improved agroforestry systems and reduction in deforestation are key actions included in Colombia's NDC. Thailand excludes land use, land-use change, and forestry in its NDC but domestic policies include reforestation, forest conservation, rehabilitation of watershed areas, and tree plantation in the degraded lands (ONEP 2015). India has no emission reduction target for agriculture but there are a few actions included in its NDC, such as

Table 6. Mitigation potential of agriculture sub-sector included in the investment cases.

Mitigation options	GHG mitigation target	Sub-sector GHG mitigation potential
Improved rice cultivation in Thailand	1.66 Mt CO_2e cumulative over the 5 years lifespan of the NSP (NAMA facility)	8.08 Mt CO_2e yr^{-1} (Roe *et al* 2021)
Precision nutrient management in India	No target	17.5 Mt CO_2 yr^{-1} (Sapkota *et al* 2019)
Improved rice cultivation in Vietnam	16 Mt CO_2eq by 2030 ($\sim$1.6 Mt CO_2-eq yr^{-1}) (NDC)	12.12 Mt CO_2e yr^{-1} (Roe *et al* 2021)
Low emission dairy in Kenya	8.08 Mt CO_2eq over 10 years (Kenya Dairy NAMA Proposal) • Increased dairy productivity: 4.14 Mt CO_2eq • Energy efficiency in processing: 2.96 Mt CO_2eq • Household biogas adoption: 0.98 Mt CO_2eq	5.28–12.98 Mt CO_2 yr^{-1} with interventions applied to the entire dairy sector (FAO 2017)
Low emission bovine production in Colombia	Grazing practices: 6.72 Mt CO_2eq Grazing practices + ecological restoration: 34.2 Mt CO_2eq by 2030 (NAMA)	Grazing management: 2.87 Mt CO_2 yr^{-1} and Reforestation: 325.2 Mt CO_2 yr^{-1} (Griscom *et al* 2021)

Note: Griscom *et al* (2021), Roe *et al* (2021) and Sapkota *et al* (2019) estimated the economic potential of GHG mitigation from the sub-sectors, FAO (2017) estimated technical potential in the Kenyan dairy sector using generic modeling exercise.

solarization of irrigation pumps, promotion of biogas digesters, use of SHC for crop nutrient management, and afforestation and forest management, that support GHG emissions reduction from the agriculture and allied sectors.

Table 6 presents the mitigation potential of the agriculture sub-sector included in the investment cases. Improved paddy rice cultivation in Thailand and Vietnam can contribute up to 8.08 and 12.12 Mt CO_2 yr^{-1} emission reduction, respectively (Roe *et al* 2021). This mitigation potential may differ with the method of estimation and type of mitigation options included for emission reduction. These are ambitious mitigation targets for rice cultivation but they are possible. For example, AWD and mid-season drainage on 1.2 million ha can achieve 65% of Vietnam's unconditional mitigation goal for the agriculture sector with an average net benefit of US$ 193 ha^{-1} (Tran *et al* 2019). While the mitigation from an additional 1.5 million ha converted to AWD and 1 million ha of ICM is a sizeable contribution of 38% towards Vietnam's conditional mitigation target from the agriculture sector, a considerable amount of mitigation still needs to be achieved by other agricultural actions. The average emission reduction cost of AWD ranges from US$ −17 to −24.6 per tCO_2eq (Escobar *et al* 2019). Investment cases in Thailand and Vietnam combine AWD with laser land leveling, straw management, and management of fertilizer application that can further contribute to GHG reduction without a decrease in yields and income from paddy rice cultivation.

India can realize a large gain from a small improvement in fertilizer use efficiency by the application of precision nutrient management based on the information provided in the SHC. The GHG mitigation potential of reduced fertilizer N consumption due to the adoption of precision nutrient management technologies in India is 17.5 Mt CO_2 yr^{-1} with a cost saving of US$ 91 per tCO_2 (Sapkota *et al* 2019). Increasing efficiency in fertilizer use can generate both economic and environmental benefits for the country. Currently, India allocates more than US$ 8 billion in fertilizer subsidy (2020–21). For example, 8%–10% reduction in fertilizer use with the application of SHC information can save about one billion US$ subsidy and reduce 7.34–9.18 Mt CO_2eq emissions.

Kenya's dairy sector emissions reduction potential ranges from 2.28 to 12.98 Mt CO_2 yr^{-1} (FAO 2017). Low-cost options include improved feed with the use of fodder and grasses and reducing milk loss and waste in collection and cooling centers. Key GHG mitigation options for the livestock sector in Kenya are improved feed with fodder and hay production (1.57 Mt CO_2eq yr^{-1}), manure management using biogas plants (0.09 Mt CO_2eq yr^{-1}), breed improvement (1.2 Mt CO_2eq yr^{-1}), dairy processing plants retrofit (0.14 Mt CO_2eq yr^{-1}), and reduction of milk loss and waste (2.9 Mt CO_2eq yr^{-1}). The cost of GHG emissions abatement using these options ranges from US$ −63/tCO_2 (improved feed) to US$ +80/tCO_2 (dairy processing plants retrofit) (Khatri-Chetri *et al* 2020). These estimates show that Kenya has a large potential to reduce GHG emissions from the livestock sector with cost-saving benefits.

The GHG mitigation potential from reforestation and grazing land management in Colombia is 325.2 and 2.87 Mt CO_2 yr^{-1}, respectively (Griscom *et al* 2021). Well-managed silvopastoral systems in the country can improve overall productivity, carbon sequestration and provide additional economic benefits for livestock farmers. Carbon sequestration rates of silvopastoral systems vary between 1.0 and 5.0 tonnes carbon ha^{-1} yr^{-1} depending on the climate, soil conditions, pasture type, and tree species (Ibrahim *et al* 2009). Colombia has 34.4 million ha of pasture lands of which 30% are classified as unmanaged (DANE 2014). Expansion of silvopastoral systems and improved management of unmanaged pastures offer synergies in both GHG mitigation and adaptation benefits in the country.

4.4. Addressing gaps in mitigation finance

Five investment cases evaluated in this study provide good examples of addressing gaps in mitigation finance by leveraging funds from different sources, bundling financial instruments, and investing in mitigation options that also provide adaptation benefits. Thai rice NAMA and Kenya's dairy NAMA aim to address the financing gap for GHG mitigation by channeling additional sources of finance. They integrate blended finance and PPP to increase private sector investment in mitigation options. They also target unlocking commercial credit using blended finance mechanisms. These two projects use grants to offer technical assistance to loan beneficiaries and local financial institutions, partnering with climate finance institutions (e.g. Green Climate Fund and NAMA facility) to establish a concessional credit line for commercial banks, and guaranteeing the loan portfolio for private sector investors. This helps to de-risk investments and catalyzes private capital by standardizing requirements of public capital, realigning returns, and leveraging expectation (by guarantees, subsidized interest rate, or offsetting the cost of capital), and increasing the effective application of risk reduction tools (Millan *et al* 2019).

Government finance in climate-smart rice cultivation in Vietnam and SHC scheme in India also inspire private sectors' investment. The SHC scheme in India promotes private agri-entrepreneurs for building mobile/mini soil testing labs and village-level soil testing facilities with co-investment. Livestock NAMA of Colombia plans to develop a public–private financing alliance including the National Federation of Cattle Ranchers, Global Environment Fund, and bilateral and multilateral financing institutions. In all investment cases, integration of diverse financial sources is not only supporting to leverage finance but also expertise and capabilities for diversifying, managing, and rebalancing risk-return profiles. This coordination of finance also aligns mitigation funds with development assistance and guides investment to better target strategic needs. They also followed a widely used project-based approach which is easy to implement and monitor performances. An effective way to utilize mitigation finance in agriculture is to bundle one or more financial instruments with technical assistance (Sadler *et al* 2016). Investment cases considered in this study are using a variety of financing instruments, such as the provision of subsidized loans, grants, guarantees for loans, and technical assistance facilities, to offer more comprehensive solutions to financial institutions and other stakeholders to help improve mitigation financing. The bundling of several instruments at a time may increase the efficiency of resource use and reduce the risk of investment.

Mitigation measures in agriculture must provide direct benefits to farmers and other value chain actors and contribute to agriculture development, food security, and trade to gain policy supports and investment (Wollenberg and Negra 2011, Dickie *et al* 2014). The evaluation of sustainability indicators of investment cases revealed a large economic benefit to the farmers by improving farm productivity, input use efficiency, and income. These are some of the key indicators of building resilient agriculture to climate change. In the absence of incentives for GHG reduction to the farmers and other value chain actors, these benefits can motivate them to invest in mitigation options in agriculture.

5. Conclusions

Achieving the target of limiting global warming, SDGs and net-zero emissions requires a combination of policies, incentives and technical supports, and coordination of actions across multiple stakeholders. Low emission agriculture development will not be possible without significantly increasing the amount of investment in mitigation actions across the regions and agriculture sub-sectors. But, access to finance for climate action in agriculture is a major challenge due to low investment priority and reluctance of global and national financial institutions. This paper evaluated innovative financial mechanisms and instruments that integrate climate finance, agriculture development budgets, and private sector investments to improve and increase farmers' and other value chain actors' access to finance while delivering environmental, economic, and social benefits. This assessment of investment cases provides rich information to design and implement mitigation actions in agriculture through unlocking additional sources of public and private capital, strengthening the links between financial institutions, farmers, and agribusiness, and coordination of actions across multiple stakeholders. These investment cases could help to develop new finance mechanisms that meet the needs of a large number of smallholder farmers and SMEs to implement the mitigation options.

The innovative financial mechanisms and instruments used in the investment cases can accommodate the different risks-return profiles of all stakeholders of the project. For instance, Thai Rice and Kenya Dairy NAMAs are using layered capital structures to meet the risk appetite of each of their investors. Climate-smart rice production program in Vietnam and SHC scheme in India promote PPP model to leverage private capital in climate actions. All investment cases expand support for existing agricultural best practices, integrate forestry and agricultural actions to avoid land-use change, and support the transition to market-based solutions. These are the promising investment cases that can be replicated to facilitate the rapid advancement and scaling-up of climate finance in agriculture and allied sectors.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

Thanks to Eva Wollenberg (Lini), Low Emissions Development Flagship Leader of CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), for her guidance and inputs to conduct this research. Authors also thank the anonymous reviewers for their comments and contributions. This work was undertaken as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is a strategic partnership of CGIAR and Future Earth. CCAFS' work is supported by CGIAR Fund Donors and through bilateral funding agreements. For details please visit https://ccafs.cgiar.org/donors. The views expressed in the document cannot be taken to reflect the official opinions of CGIAR, Future Earth, or donors.

ORCID iDs

Arun Khatri-Chhetri https://orcid.org/0000-0002-3811-0462
Tek B Sapkota https://orcid.org/0000-0001-5311-0586
Katherine M Nelson https://orcid.org/0000-0001-9242-246X

References

Allen J M and Sander B O 2019 *The Diverse Benefits of Alternate Wetting and Drying (AWD)* (Los Baños: International Rice Research Institute (IRRI)) (available at: https://hdl.handle.net/10568/101399) (Accessed 15 May 2021)

Allen J *et al* 2020 Rice straw management effects on greenhouse gas emissions and mitigation options *Sustainable Rice Straw Management* ed M Gummert *et al* (Berlin: Springer) (https://doi.org/10.1007/978-3-030-32373-8_9)

Arango J *et al* 2020 Ambition meets reality: achieving GHG emission reduction targets in the livestock sector of Latin America *Front. Sustain. Food Syst.* **4** 1–9

Aryal J P, Mehrotra M B, Jat M L and Sidhu H S 2015 Impacts of laser land leveling in rice-wheat systems of the North-Western Indo-Gangetic plains of India *Food Secur.* **7** 725–38

Aynekulu E, Suber M, van Noordwijk M, Arango J, Roshetko J M and Rosenstock T S 2020 Carbon storage potential of silvopastoral systems on Colombia *Land* **9** 309

Beach R H, Creason J, Ohrel S B, Ragnauth S, Ogle S, Li C, Ingraham P and Salas W 2016 Global mitigation potential and costs of reducing agricultural non-$C0_2$ greenhouse gas emissions through 2030 *J. Integr. Environ. Sci.* **12** 87–105

Buchner B, Clark A, Falconer A, Macquarie R, Meattle C, Tolentino R and Wetherbee C 2019 *Global Landscape of Climate Finance* (London: Climate Policy Initiative) (available at: https://climatepolicyinitiative.org/publication/global-climate-finance-2019/) (Accessed 15 May 2021)

Buresh R J, Castillo R L, Torre J C D, Laureles E V, Samson M I, Sinohin P J and Guerra M 2019 Site-specific nutrient management for rice in the Philippines: calculation of field-specific fertilizer requirements by Rice Crop Manager *Field Crops Res.* **239** 56–70

Campbell B M, Hansen J, Rioux J, Stirling C M, Twomlow S and Wollenberg E 2018 Urgent action to combat climate change and its impact (SDG 13): transforming agriculture and food systems *Curr. Opin. Environ. Sustain.* **34** 13–20

Chidthaisong A, Cha-Un N, Rossopa B, Buddaboon C, Kunuthai C, Sriphirom P, Towprayoon S, Tokida T, Padre A T and Minamikawa K 2018 Evaluating the effects of alternate wetting and drying (AWD) on methane (CH_4) and nitrous oxide (N_2O) emissions from a paddy field in Thailand *Soil Sci. Plant Nutr.* **64** 31–38

DANE 2014 *Censo Nacional Agropecuario 2014* (Bogotá: Departamento Nacional de Estadística)

Dickie A, Streck C, Roe S, Zurek M, Haupt F and Dolginow A 2014 Strategies for mitigating climate change in agriculture: abridged report *Climate Focus and California Environmental Associates, prepared with the support of the Climate and Land Use Alliance* Report and supplementary materials (available at: www.agriculturalmitigation.org) (Accessed 15 May 2021)

Dijk S, Wilkes A and Odhong' C 2018 The potential for commercial hay production in Kenya CCAFS Info Note (Wageningen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)) (available at: https://hdl.handle.net/10568/93176) (Accessed 15 May 2021)

Edmunds D, Sasser J and Wollenberg E 2013 A gender strategy for pro-poor climate change mitigation *CCAFS Working Paper No. 36* (Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)) (available at: https://cgspace.cgiar.org/bitstream/handle/10568/27765/WorkingPaper36.pdf) (Accessed 15 May 2021)

Escobar C D, Grosjean G, Läderach P, Nghia T D, Sander B O, McKinley J, Sebastian L and Tapasco J 2019 Reviewing Vietnam's nationally determined contribution: a new perspective using the marginal cost of abatement *Front. Sustain. Food Syst.* **3** 14

FAO 2017 *Options for Low-Emission Development in the Kenya Dairy Sector—Reducing Enteric Methane for Food Security and Livelihoods* (Rome: Food and Agriculture Organisation of the United Nations) p 43

Farnworth C R, Ha T T, Sander B O, Wollenberg E, de haan N C and McGuire S 2017 Incorporating gender into low-emission development: a case study from Vietnam *Gend. Technol. Dev.* **21** 2–30

Fishman R, Kishore A, Rothler Y, Ward P S, Jha S and Singh R K P 2016 Can information help reduce imbalanced application of fertilizer in India: experimental evidence from Bihar IFPRI Discussion Paper 01517 (Washington, DC)

Frank S *et al* 2017 Reducing greenhouse gas emissions in agriculture without compromising food security *Environ. Res. Lett.* **12** 105004

Gallina A 2016 Gender dynamics in dairy production in Kenya: a literature review *Working Paper No. 182* (Copenhagen:

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)) (available at: https://hdl.handle.net/10568/77727) (Accessed 20 May 2021)
Garg M R, Sherasia P L, Phondba B T and Makkar H P 2016 Greenhouse gas emission intensity based on lifetime milk production of dairy animals, as affected by the ration-balancing program *Anim. Prod. Sci.* **58** 1027–42
Gartaula H, Sapkota T, Khatri-Chhetri A, Prasad G and Badstue L 2020 Gendered impacts of greenhouse gas mitigation options for rice cultivation in India *Clim. Change* **163** 1045–63
Gernaat D E H J, Calvin K, Lucas P L, Luderer G, Otto S A C, Rao S, Strefler J and van Vuuren D P 2015 Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios *Glob. Environ. Change* **33** 142–53
Gill G J 2014 An assessment of the impact of laser-assisted precision land leveling technology as a component of climate-smart agriculture in the state of Haryana, India (available at: https://hdl.handle.net/10568/65078) (Accessed 20 May 2021)
GoI 2016 India's intended nationally determined contribution: working towards climate justice (Government of India) (available at here)
GoV 2017 The second biennial updated report of Vietnam to the United Nations framework convention (Socialist Republic of Vietnam, Ministry of Natural Resources and Environment) (available at: https://unfccc.int/sites/default/files/resource/97620135_Viet%20Nam-BUR2-1-Viet%20Nam%20-%20BUR2.pdf) (Accessed 22 June 2021)
GoV 2020 Updated nationally determined contribution (The Socialist Republic of Vietnam) (available at here)
Government of Kenya 2020 Kenya's updated nationally determined contribution (Government of Kenya) (available here)
Gromko D and Abdurasalova G 2018 Climate change mitigation and food loss and waste reduction: exploring the business case CCAFS Working Paper No. 246 (available at: https://hdl.handle.net/10568/100165) (Accessed 20 May 2021)
Grossi G, Goglio P, Vitali A and Williams A G 2019 Livestock and climate change: impact of livestock on climate and mitigation strategies *Anim. Front.* **9** 69–76
Guarnaschelli S, Limketkai B and Vandeputte P 2018 Financing sustainable land use *Unlocking Business Opportunities in Sustainable Land Use with Blended Finance* (London: KOIS INVESTMENT) 1–96
Hamid R G and Blanchard R E 2018 An assessment of biogas as a domestic energy source in rural Kenya: developing a sustainable business model *Renew. Energy* **121** 368–76
Herrero M *et al* 2016 Greenhouse gas mitigation potentials in the livestock sector *Nat. Clim. Change* **6** 452–61
Hristov A N *et al* 2013a Mitigation of methane and nitrous oxide emissions from animal operations: a review of enteric methane mitigation options *J. Anim. Sci.* **91** 5045–69
Hristov A N *et al* 2013b Mitigation of greenhouse gas emissions in livestock production—a review of technical options for non-CO_2 emissions *FAO Animal Production and Health Paper No. 177* ed (Rome: FAO)
Ibrahim M, Guerra L, Casasola F and Neely C 2009 Importance of silvopastoral systems for mitigation of climate change and harnessing environmental benefits *Grassland Carbon Sequestration: Management, Policy and Economics* ed M Abberton *et al* (Rome: FAO) 189–96
IDEAM 2016 Inventario Nacional y Departamental de Gases de Efecto Invernadero (GEI) de Colombia *Tercera Comunicación Nacional de Cambio Climático de Colombia* (Bogotá: IDEAM, PNUD, MADS, DNP, CANCILLERÍA, FMAM)
IPCC 2019 Summary for Policymakers Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems ed P R Shukla, J Skea, E C Buendia, V Masson-Delmotte, H O Pörtner, D C Roberts, P Zhai, R Slade, S Connors, R van Diemen, M Ferrat, E Haughey, S Luz, S Neogi, M Pathak, J Petzold, J P Pereira, P Vyas, E Huntley, K Kissick, M Belkacemi and J Malley (available here)
Jat H S, Datta A, Choudhary M, Yadav A K, Choudhary V, Sharma P C, Gathala M K, Jat M L and McDonald A 2019 Effect of tillage, crop establishment and diversification on soil organic carbon, aggregation, aggregate association carbon and productivity in cereal systems in semi-arid northwest India *Soil Tillage Res.* **190** 128–38
Jiang Y *et al* 2019 Acclimation of methane emissions from rice paddy fields to straw addition *Sci. Adv.* **5** eaau9038
Kantachote D, Nunkaew T, Kantha T and Chaiprapat S 2016 Biofertilizers from rhodopseudomonas palustris strains to enhance rice yields and reduce methane emissions *Appl. Soil Ecol.* **100** 154–61
Kashangaki J and Ericksen P 2018 Cost-benefit analysis of fodder production as a low emissions development strategy for the Kenyan dairy sector *ILRI Project Report* (Nairobi: ILRI) (available at: https://hdl.handle.net/10568/97426) (Accessed 20 May 2021)
Khatri-Chhetri A, Regmi P P, Chanan N and Aggarwal P K 2020a Potential of climate-smart agriculture in reducing women farmers' drudgery in high climatic risk areas *Clim. Change* **158** 29
Khatri-Chhetri A, Wilkes A and Odhong C 2020b Mitigation options and finance for transition to low-emissions dairy in Kenya *CCAFS Working Paper No. 329* (Wageningen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)) (available at: https://hdl.handle.net/10568/110568) (Accessed 20 May 2021)
Kishore A, Alvi M and Krupni T J 2021 Development of balanced nutrient management innovations in South Asia: perspectives from Bangladesh, India, Nepal, and Sri Lanka *Glob. Food Secur.* **28** 100464
Kristjanson P, Waters-Bayer A, Johnson N, Tipilda A, Njuki J, Baltenweck I, Grace D and MacMillan S 2014 Livestock and women's livelihoods: a review of the recent evidence Gender in agriculture: closing the knowledge gap ed A R Quisumbing *et al* (Rome: FAO)
Landholm D M, Pradhan P, Wegmann P, Sánchez M A R, Salazar J C S and Kropp J P 2019 Reducing deforestation and improving livestock productivity: greenhouse gas mitigation potential of silvopastoral systems in Caqueta *Environ. Res. Lett.* **14** 114007
Liu X, Zhou T, Liu Y, Zhang X, Li L and Pan G 2019 Effect of mid-season drainage on CH_4 and N_2O emission and gain yield in rice ecosystem: a meta-analysis *Agric. Water Manage.* **213** 1028–35
Lyng K-A, Bjerkestrand M, Stensgard A E, Callewaert P and Hanssen O J 2018 Optimizing anaerobic digestion of manure resources at a regional level *Sustainability* **10** 286
MAFW 2020 Implementation of soil health card scheme (Ministry of Agriculture and Farmers Welfare, Government of India)
MAFW 2021 Implementation of soil health card scheme (New Delhi: Ministry of Agriculture and Farmers Welfare)
MALF 2017a Kenya climate-smart agriculture strategy 2017–2026 The Ministry of Agriculture, Livestock and Fisheries, Republic of Kenya, Nairobi, Kenya (available at: www.adaptation-undp.org/sites/default/files/resources/kenya_climate_smart_agriculture_strategy.pdf) (Accessed 21 May 2021)
MALF 2017b Kenya's dairy national appropriate mitigation action (NAMA) (Ministry of Agriculture, Livestock and Fisheries, State Department of Livestock, Republic of Kenya)
McKinsey 2020 Agriculture and climate change: reducing emissions through improved farming practices (McKinsey and Company) (available here)
Millan A, Limketkai B and Guarnaschelli S 2019 Financing the transformation of food systems under a changing climate CCAFS Report (Wageningen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)) (available at: https://hdl.handle.net/10568/101132) (Accessed 21 May 2021)

MNRE 2018 The second biennial updated report of Thailand to the United Nations framework convention Kingdom of Thailand, Ministry of Natural Resources and Environment (available at: www4.unfccc.int/sites/SubmissionsStaging/NationalReports/Documents/347251_Thailand-BUR2-1-SBUR%20THAILAND.pdf) (Accessed 21 May 2021)

MoEF 2020 Kenya's updated nationally determined contribution. Ministry of Environment and Forestry *Communication to the United Nations Framework Convention on Climate Change (UNFCCC)*

MONRE 2015 Technical report on Vietnam's intended nationally determined contribution *Ministry of Natural Resources and Environment (MONRE)* (Hanoi)

Moring A *et al* 2021 Nitrogen challenges and opportunities for agricultural and environmental science in India *Front. Sustain. Food Syst.* **5** 1–16

NAMA Facility 2020 Thai Rice NAMA (available at: www.nama-facility.org/projects/thailand-thai-rice-nama/) (Accessed 21 May 2021)

Nelson A, Wassmann R, Sander B O and Palao L K 2015 Climate-determined suitability of the water-saving technology 'alternate wetting and drying' in rice systems: a scalable methodology demonstrated for a Province in the Philippines *PLoS One* **10** e0145268

OECD 2019 *Enhancing Climate Change Mitigation through Agriculture* (Paris: OECD Publishing) (https://doi.org/10.1787/e9a79226-en)

ONEP 2015 Thailand's intended nationally determined contribution (INDC) (Bangkok: Office of Natural Resources and Environmental Policy and Planning Ministry of Natural Resources and Environment) pp 1–6

Palmer N 2015 Bovine intervention: Colombia prepares to give unsustainable cattle production the hoof (available at: https://blog.ciat.cgiar.org/bo-vine-intervention/) (Accessed 21 May 2021)

Pauw W P, Castro P, Pickering J and Bhasin S 2020 Conditional nationally determined contributions in the Paris Agreement: foothold for equity or Achilles heel? *Clim. Policy* **20** 468–84

Poore J and Nemecek T 2018 Reducing food's environmental impacts through producers and consumers *Science* **360** 987–92

Richard M and Sander O 2014 Alternative wetting and drying in irrigated rice: implementation guidance for policymakers and investors Practice Brief. CCAFS and IRRI (available at: https://hdl.handle.net/10568/35402) (Accessed 25 May 2021)

Richards M B, Wollenberg E and Buglion-Gluck S 2015 Agriculture's contributions to national emissions *CCAFS Info Brief* (Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (available at: https://hdl.handle.net/10568/68841) (Accessed 25 May 2021)

Richards M *et al* 2016 How countries plan to address agricultural adaptation and mitigation: an analysis of intended nationally determined contributions CGIAR Research Program on Climate Change (available at: https://hdl.handle.net/10568/73255) (Accessed 25 May 2021)

Richards M, Arslan A, Cavatassi R and Rosenstock T 2019 Climate change mitigation potential of agricultural practices supported by IFAD investments: an ex-ante analysis (Rome: The International Food and Agriculture Development Research Series, IFAD)

Roe S *et al* 2021 Land-based measures to mitigate climate change: Potential and feasibility by country *Global Change Biol.* **27** 6025–58

Ruden A 2018 Model of enteric methane emissions supports climate change mitigation in Colombia's cattle sector *CCAFS Info Note* (Wageningen, Netherlands) (available at: https://hdl.handle.net/10568/97097) (Accessed 25 May 2021)

Sadler M P 2016 Making climate finance work in agriculture (Washington, DC: World Bank Group) (available at: http://documents.worldbank.org/curated/en/986961467721999165/Making-climate-finance-work-in-agriculture) (Accessed 25 May 2021)

Sander B O, Schneider P, Romasanta R, Samoy-Pascual K, Sibayan E B, Asis C A and Wassmann R 2020 Potential of alternate wetting and drying irrigation practices for the mitigation of ghg emissions from rice fields: two cases in Central Luzon (Philippines) *Agriculture* **10** 350

Sapkota T B *et al* 2021 Crop nutrient management using nutrient expert improves yield, increases farmers' income and reduces greenhouse gas emissions *Sci. Rep.* **11** 1564

Sapkota T B, Jat M L, Shankar V, Singh L K, Rai M, Grewal M S and Stirling C M 2015 Tillage, residue and nitrogen management effects on methane and nitrous oxide emission from rice-wheat system of Indian Northwest Indo-Gangetic Plains *J. Integr. Environ. Sci.* **12** 31–46

Sapkota T B, Vetter S H, Jat M L, Sirohi S, Shirsath P B, Singh R, Jat H S, Smith P, Hillier J and Stirling C M 2019 Cost-effective opportunities for climate change mitigation in Indian agriculture *Sci. Total Environ.* **655** 1342–54

Sharma S, Thind H S, Singh Y, Sidhu H S, Jat M L and Parihar C M 2019 Effect of crop residue retention on soil carbon pools after 6 years of rice-wheat cropping system *Environ. Earth Sci.* **78** 296

Singh B 2017 Management and use efficiency of fertilizer nitrogen in production of cereals in Indian issues and strategies *The Indian Nitrogen Assessment: Sources of Reactive Nitrogen, Environmental and Climate Effects, Management Options, and Policies* ed Y P Abrol, T K Adhya, V P Aneja, N Raghuram, H Pathak and U Kulshrestha *et al* (Cambridge: Elsevier) pp 9–28

Steiner A *et al* 2020 *Actions to Transform Food Systems under Climate Change* (Wageningen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS))

Tapasco J, LeCoq J F, Ruden A, Sebastian R and Ortiz J 2019 The livestock sector in Colombia: toward a program to facilitate large-scale adoption of mitigation and adaptation practices *Front. Sustain. Food Syst.* **6** 1–17

Tariq A, Vu Q D, Jensen L S, de Tourdonnet S, Sander B O, Wassmann R, van Mai T and de Neergaard A 2017 Mitigating CH_4 and N_2O emissions from intensive rice production systems in Northern Vietnam: efficiency of drainage patterns in combination with rice residue incorporation *Agric. Ecosyst. Environ.* **249** 101–11

Tesfaye K, Takele R, Sapkota T B, Khatri-Chhetri A, Solomon D, Stirling C and Albanito F 2021 Model comparison and quantification of nitrous oxide emission and mitigation potential from maize and wheat fields at a global scale *Sci. Total Environ.* **782** 146696

Thornton P K and Herrero M 2010 Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics *Proc. Natl Acad. Sci.* **107** 19667–72

Thornton P K *et al* 2018 A qualitative evaluation of CSA options in mixed crop-livestock systems in developing countries *Climate Smart Agriculture, Natural Resource Management and Policy* ed L Lipper *et al* (Rome: Food and Agriculture Organization of the United Nations) vol 52 385–423

Thu T N, Phuong L B, Van T T M and Hong S N 2016 Effect of water regimes and organic matter strategies on mitigating greenhouse gas emission from rice cultivation and co-benefits in agriculture in Vietnam *Int. J. Environ. Sci. Dev.* **7** 85–90

Tirado R, Gopikrishna S R, Krishnan R and Smith P 2010 Greenhouse gas emissions and mitigation potential from fertilizer manufacture and application in India *Int. J. Agric. Sustain.* **8** 176–85

Tran D H, Hoang T N, Tokida T, Padre A and Minamikawa K 2018 Impacts of alternate wetting and drying on greenhouse gas emission from paddy field in Central Vietnam *Soil Sci. Plant Nutr.* **64** 14–22

Tran V T, Mai V T, Nguyen T D T, Le H A, Richards M B, Sebastian L, Wollenberg E, Vu D Q and Sander B O 2019 An investment plan for low-emission rice production in the Mekong River Delta region in support of Vietnam's nationally determined contribution to the Paris Agreement *CCAFS Working Paper No. 263* (available at: https://hdl.handle.net/10568/101315) (Accessed 26 May 2021)

Trinh M V, Tesfai M, Borrell A, Nagothu U S, Bui T P L and Quynh V D 2017 Effect of organic, inorganic and slow-release urea fertilizers on CH_4 and N_2O emissions from rice paddy fields *Paddy Water Environ.* **15** 317–30

USFRA 2021 Transformative investment in climate-smart agriculture unlocking the potential of our soils to help the US achieve a net-zero economy (Chesterfield, MO: US Farmers and Rancher in Action) (available at: https://usfarmersandranchers.org/wp-content/uploads/2021/02/USFRA-Transformative-Investment-Report.pdf) (Accessed 26 May 2021)

van Wijk M T, Merbold L, Hammond J and Butterbach-Bahl K 2020 Improving assessments of the three pillars of climate smart agriculture: current achievements and ideas for the future *Front. Sustain. Food Syst.* **4** 1–14

Vermeulen S *et al* 2016 *The Economic Advantage: Assessing the Value of Climate Change Actions in Agriculture* (Rome: IFAD) (available at: https://hdl.handle.net/10568/77628) (Accessed 26 May 2021)

Vo T B T, Wassmann R, Mai V T, Vu D Q, Bui T P L, Vu T H, Dinh Q H, Yen B T, Asch F and Sander B O 2020 Methane emission factors from Vietnamese rice production: pooling data of 36 field sites for meta-analysis *Climate* **8** 74

Vu Q D, de Neergaard A, Tran T D, Hoang Q Q, Ly P, Tran T M and Jensen L S 2015 Manure, biogas digester and crop residue management affect methane gas emissions from rice paddy fields on Vietnamese smallholder livestock farms *Nutr. Cycl. Agroecosyst.* **103** 329–46

WBCSD 2020 Accelerating business solutions for climate and nature report I: mapping nature-based solutions and natural climate solutions (Geneva: World Business Council for Sustainable Development) (available at: https://docs.wbcsd.org/2020/12/WBCSD-Accelerating-Business-Solutions-for-Climate-and-Nature.pdf) (Accessed 27 May 2021)

Wilkes A, van Dijk S and Odhong' C 2018 The potential for reduced consumption of high emission energy in Kenya's dairy sector *CCAFS Info Note* (available at: https://hdl.handle.net/10568/93174) (Accessed 27 May 2021)

Wilkes A, Wassie S E, Vorlaufer M, Odhong' C and van Dijk S 2020a Further evidence that gender matters for GHG mitigation in the dairy sector: analysis of survey data from central Kenya highlights interactive effects of gender and farm management practices on milk yield and GHG emission intensity (Wageningen: CCAFS (available at: https://hdl.handle.net/10568/107156) (Accessed 4 June 2021)

Wilkes A, Wassie S, Odhong C, Fraval S and van Dijk S 2020b Variation in the carbon footprint of milk production on smallholder dairy farms in central Kenya *J. Clean. Prod.* **265** 121780

Wollenberg E *et al* 2016 Reducing emissions from agriculture to meet the 2 °C target *Glob. Change Biol.* **22** 3859–64

Wollenberg E and Negra C 2011 Next steps for climate change mitigation in agriculture *CCAFS Policy Brief 2* (Copenhagen: CCAFS) (available at: https://hdl.handle.net/10568/10237) (https://doi.org/10.1073/pnas.1019018108) (Accessed 4 June 2021)

World Bank Group 2019 *Bangladesh Climate-Smart Agriculture Investment Plan: Investment Opportunities in the Agriculture Sector's Transition to a Climate Resilient Growth Path* (Washington, DC: World Bank) (available at: https://openknowledge.worldbank.org/handle/10986/32742) (Accessed 4 June 2021)

World Bank, CIAT and CATIE 2014 Climate-smart agriculture in Colombia *CSA Country Profiles for Latin America Series* (Washington DC: The World Bank Group)