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Climate change mitigation potential of agricultural practices supported by IFAD investments

An ex ante analysis

by
Meryl Richards
Aslihan Arslan
Romina Cavatassi
Todd Rosenstock

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Abstract

International discussions on climate change increasingly recognize the importance of agriculture in adaptation and mitigation efforts. Adaptation has been generally prioritized in the most vulnerable countries, where a failure to adapt can constitute a threat to food security. However, synergies between adaptation and mitigation exist in many cases. Climate-smart agriculture, an approach to agriculture that sustainably increases productivity, enhances adaptation and mitigates emissions where possible, is gaining ground. The potential to harness mitigation co-benefits in the IFAD portfolio remains unexploited, potentially leading to unrecognized impact and lost opportunities to access climate finance. This study estimates the mitigation potential of agricultural practices supported by IFAD's current investments in agricultural development to provide guidance for the design of future IFAD investments. We use data from field studies in the scientific literature to estimate the effects of a large set of agricultural practices promoted by IFAD (and other development agencies) on soil organic carbon stocks, nitrous oxide emissions from soils, and methane emissions from rice paddies. Our findings identify soil and rice management practices with the largest mitigation potential and those that can potentially increase emissions; discuss uncertainties in mitigation analyses; and provide recommendations to improve monitoring of mitigation benefits for project design and implementation.

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1 Objectives and background

1.1 Purpose and objectives of the study

International discussions on climate change increasingly recognize the importance of agriculture in adaptation and mitigation efforts. Adaptation has generally been prioritized by the most vulnerable countries, where a failure to adapt can constitute a threat to food security. More than 90 per cent of countries in each International Fund for Agricultural Development (IFAD) region have included adaptation in the agriculture sector as a priority in their Nationally Determined Contributions (NDCs) to the Paris Agreement, and 58 per cent have included agriculture in their mitigation targets. IFAD is taking steps to align investments with the adaptation priorities that countries have outlined in NDCs or other national development programmes.

However, synergies between adaptation and mitigation exist in many cases. Climate-smart agriculture, an approach to agriculture that sustainably increases productivity, enhances adaptation and mitigates emissions where possible, is gaining ground. In the IFAD portfolio, the potential to harness mitigation co-benefits remains unexploited. Because potential synergies between adaptation and mitigation may not have been explored, this may lead to unrecognized impact and lost opportunities to access climate finance.

The purpose of this study is to inform discussions on improved design, targeting and monitoring of IFAD investments and to highlight interventions in regions where IFAD is working that can create both mitigation and food security benefits. The analysis makes use of the Climate-Smart Agriculture Compendium, a comprehensive database of the impacts of 102 agricultural practices on 53 indicators of the mitigation, adaptation and food security objectives of climate-smart agriculture (Rosenstock et al. 2016). The database is a collaborative effort of the World Agroforestry Centre (ICRAF), the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS) and the Food and Agriculture Organization of the United Nations (FAO).

The study objectives are to:

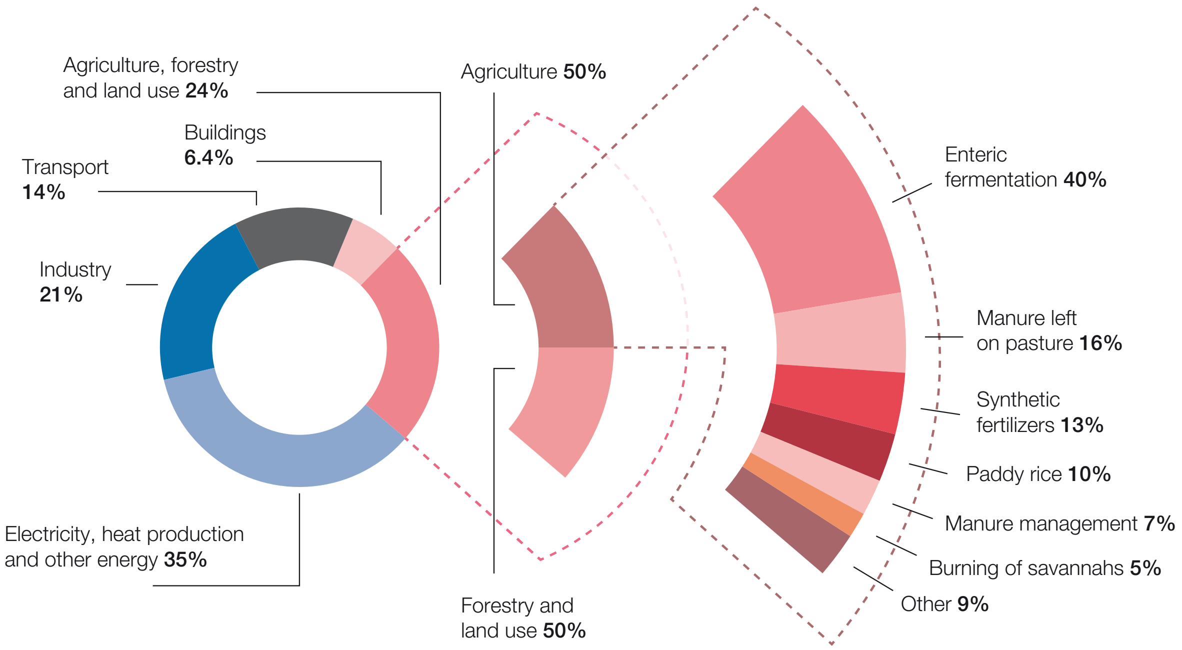
- Estimate the mitigation potential of a large set of agricultural practices promoted by IFAD investments using data from analogous field studies in the scientific literature;
- Provide guidance for the design of future IFAD investments by highlighting food security investments likely to have mitigation co-benefits and investments at risk of increasing greenhouse gas (GHG) emissions; and
- Contribute to IFAD's efforts to monitor the mitigation potential of the projects it funds.

1.2 Background on greenhouse gas emissions from agriculture and mitigation opportunities

Agriculture (excluding forestry and other land uses) contributes approximately 12 per cent of global GHG emissions. Methane (CH_4) and nitrous oxide (N_2O) are the primary GHGs produced by agricultural activities, comprising about 55 per cent and 45 per cent of emissions from agriculture, respectively (FAO 2017). The global warming potentials of CH_4 and N_2O oxide are 25 and 298 times that of carbon dioxide (CO_2), respectively (IPCC 2007). Global warming potential is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time (usually 100 years), relative to the emissions of 1 ton of CO_2.

There are four primary sources of GHG emissions from agriculture: enteric fermentation, livestock manures, fertilizers and paddy rice. Enteric fermentation – digestion of carbohydrates by ruminant livestock – is the largest contributor of CH_4 from agricultural systems (figure 1), contributing 40 per cent of agricultural GHG emissions. The second largest source of agricultural GHG emissions (16 per cent of agricultural GHG) is management and storage of livestock manure, which produces both CH_4 and N_2O. Synthetic nitrogen fertilizers are the third largest source (13 per cent of GHG emissions from agriculture) and the largest contributor of N_2O, which is created when nitrogen not taken up by crops undergoes microbial processes in soils. Organic nitrogen-containing fertilizers such as manure and compost are also sources of N_2O emissions. Flooded (paddy) rice cultivation produces CH_4 through anaerobic decomposition of organic materials (such as crop residues) in the rice paddy, contributing around 10 per cent of total agricultural GHG emissions.

Figure 1 Agriculture and land use currently contribute about 24 per cent of global GHG emissions; about half of that (12 per cent) is from agriculture, and the other half from other land use



Source: CDP (2015).

In addition to being sources of GHG emissions, farms also have the potential to act as "sinks" for CO_2 – in other words, to remove carbon from the atmosphere and store it in soils or woody vegetation. This study considered interventions that could mitigate climate change by sequestering carbon in agricultural soils as well as those that could reduce CH_4 and N_2O emissions. The mitigation potential of carbon sequestration in agricultural soils is large and has consequently been the focus of recent international attention such as the "4 per 1000" initiative launched at the 21st Conference of the Parties (COP 21). The 4 per 1000 initiative is an international, voluntary collaboration to increase soil organic carbon (SOC) stocks by 0.4 per cent annually, enough to halt the increase in the CO_2 concentration in the atmosphere related to human activities (Minasny et al. 2017; Soussana et al. 2017). Measures that increase SOC also have strong potential synergies with food security (Frank et al. 2017). However, a number of factors make it difficult to predict how much carbon can be stored in a particular soil and whether such carbon storage will be permanent – an important consideration for climate change mitigation (box 1). The SOC mitigation potentials here should, therefore, be interpreted with caution; in most cases they represent an *upper bound* of what might be possible in practice.

The biomass carbon mitigation potential of agroforestry – the incorporation of woody perennials with crops and livestock – is also large and, though also reversible, is less subject to the uncertainties associated with carbon sequestration in soils. The dataset used for this analysis was limited to carbon stock changes in soils. To capture the full mitigation potential of agroforestry interventions, values for carbon sequestration in biomass were taken from Cardinael et al. (2018).

2 Methods

2.1 Description of the dataset

The analysis made use of an existing dataset of GHG emissions and SOC stocks extracted from publications in peer-reviewed journals. The data resulted from a review of the scientific evidence on "climate-smart" agricultural practices (Rosenstock et al. 2016). The review was limited to studies that: (1) were published in English before 2016; (2) were located in a developing or emerging-economy country (using criteria from the World Bank); (3) reported primary data from field measurements of GHG emissions or SOC stocks; (4) examined at least one of a pre-selected set of agricultural management practices and technologies; and (5) compared an "improved" management practice with a conventional practice (see table 1 for a description of practices). An improved practice was defined as one for which there is scientific evidence of it having benefits in terms of at least one of the following: increased yields, climate resilience and/or climate change mitigation (Rosenstock et al. 2016). The literature search and data extraction efforts were limited to studies on agricultural lands involving the measurement of agricultural GHGs; studies involving land use change (conversion of cropland to forest or vice versa, for example) were excluded. Further details on the scope of the literature search, including practices, indicators and search strings, can be found in Rosenstock et al. (2016).

After initial data extraction, studies were eliminated from the dataset if they did not meet criteria for data quality, including: (1) study duration of at least two years for soil carbon (C) measurements; and (2) use of an unfertilized control to estimate background emissions for N_2O measurements. Ideally, changes in soil carbon stocks should be measured over a period of at least 20 years (the Intergovernmental Panel on Climate Change (IPCC) time dependence factor for changes in soil carbon stock), and fertilizer-induced N_2O emissions measured for an entire year. However, we included shorter-term measurements in our dataset because long-term soil carbon and N_2O measurements are rare in developing countries. To calculate changes in soil carbon stock, data on cumulative carbon stocks from the surface to the deepest soil layer reported by each study were used for the analysis.

The final dataset included data from 108 studies of SOC stock changes, 51 studies of CH_4 emissions from paddy rice and 38 studies of N_2O emissions from fertilizer application (table 2). Several studies on paddy rice contained data on both CH_4 and N_2O emissions; these were analysed separately. The dataset did not contain a sufficient number of studies on water management, irrigation, pasture management, improved livestock diets, manure management or biogas to calculate soil carbon stock change or emission rates. The mitigation potential of IFAD investments in pasture improvement was estimated using a global review by Conant et al. (2017). However, in addition to a lack of empirical evidence on mitigation potential, IFAD project design documents did not provide a sufficient level of detail to reasonably extrapolate the impact of investments in improved livestock feeding, manure management, biogas or construction of irrigation infrastructure. The mitigation potentials of these interventions are, therefore, discussed qualitatively in the text but excluded from the final analysis.

Box 1 Caveats to the SOC sequestration potential of improved agricultural practices

- The quantity of carbon stored in soil is finite. As the stock of SOC grows, it reaches a new equilibrium, and carbon sequestration ceases. The rate of increase tends to be highest in early years after a change in land use or management and slows as a new equilibrium is approached. This is important to take into account when measuring SOC stock changes. Changes measured over short time frames (i.e. 3-5 years) may not be representative of long-term trajectories of SOC stock changes. IPCC (2006) guidelines assume a time frame of 20 years for SOC to reach a new equilibrium, though few experimental studies are able to run for that long.
- It is important to distinguish between carbon sequestration in soil and avoided carbon losses from soil. Much of what we might call sequestration (implying a net removal of carbon from the atmosphere) is in fact an avoided loss. Cultivated land is often in a state of declining SOC over time; and improved practice (such as no tillage or mulching with crop residues) may reduce the rate of loss, but it does not remove CO_2 from the atmosphere and sequester it in soil.
- Carbon sequestration is reversible. Land use or soil management changes must be maintained indefinitely to maintain the increased carbon stock.
- Increasing SOC only mitigates climate change if it is an additional net transfer of carbon from atmosphere to land. The alternate fate of organic carbon inputs must be considered. For example, carbon from crop residue mulch that is locked up in soil is genuine sequestration if the crop residue would have otherwise been burned. However, if the alternate fate of the residue was as animal bedding, with the bedding eventually composted and used as a soil amendment, then a change to mulching with the residue is simply a transfer to a different carbon pool.
- Changes in SOC have a small "signal to noise" ratio. Carbon stocks vary significantly over even very small distances (meters), and increases in SOC are small relative to the total stock, making it difficult to detect changes.
- The amount of additional carbon that can be stored is strongly dependent on the initial SOC content of the soil.
- When measuring changes in SOC stocks, either by comparing measurements taken at two times or in two treatments, changes in the density of the soil must be taken into account. The current recommended method is to collect the two samples on the basis of equal soil mass, rather than equal sampling depth or equal volume.
- Depth of measurement is important. Conversion to no-till, for example, tends to increase carbon near the soil surface, while there may be less carbon in lower soil layers than when soil is tilled. Early research on no-till thus overstated its mitigation potential by not examining the baseline soil profile at depth.

Adapted from Powlson et al. (2011) and Sommer et al. (2018)

Table 1 Description of practices

Improved practice	Description of practice	Comparison (control) practice for analysis
No tillage	Minimal to no soil disturbance; crops planted using direct seeding method	Conventional or full tillage
Minimum tillage	Tillage practice that reduces soil disturbance, compared with conventional tillage	Conventional or full tillage
Increased diversity of crops	Addition of one or more crops to the cropping system, either as an intercrop or crop rotation	Monoculture, sole crop, or continuous cropping with the same crop
Organic fertilizer	Use of compost or manure as fertilizer	No fertilizer
Synthetic fertilizer	Use of synthetic nitrogen fertilizers such as ammonium nitrate or urea	No fertilizer
Crop residue management	Addition of plant-based organic material to the soil, such as mulch, green manures and crop residues (where the alternative would be removing or burning such residues); does not account for emissions created or avoided by alternative fate of residues (e.g. burning or composting)	No use of mulch or green manure; crop residues removed or burned
Agroforestry	Addition of woody perennials to the cropping system, either intercropped with primary food crops or used as improved fallows; includes live fences	No woody perennials as part of cropping system
Reduced irrigation of paddy rice	Drainage of the rice paddy for part of the growing season; includes mid-season drainage, intermittent irrigation, alternate wetting and drying, and system of rice intensification (if reduced irrigation is used)	Continuous flooding of field during growing season
N fertilizer (N_2O only)	Use of compost, manure or synthetic nitrogen fertilizers; these were combined for analysing effects on N_2O emissions due to a comparably smaller dataset of N_2O measurements	No nitrogen fertilizer
Water harvesting	Capture of rainwater or runoff for use in growing crops or watering livestock; includes dams, cisterns, terraces, bunds and planting basins	No water harvesting system (rainfed)
Irrigation	Application of water to plants; includes sprinkler, drip, flood or other irrigation systems	No irrigation (rainfed)
Pasture management	Improvement of pasture by using rotational or controlled grazing or planting pastures with new species	Conventional or unimproved pasture management
Improved diets for livestock	Improved acceptability or digestibility of feed, or use of feed supplements	Conventional or unimproved feed, or no use of supplements
Manure management	Collection, storage or treatment of manure to manage environmental impacts	Conventional manure management
Biogas	Use of anaerobic digesters to produce biogas for household or other use	No use of anaerobic digesters or biogas

Table 2 Studies per country and GHG source or sink

Country	Soil C	Paddy rice CH_4	N_2O
Argentina	4		
Brazil	26		1
Burkina Faso	1		
Chile	1		
China	20	29	25
Costa Rica	1		
Ethiopia	1		
India	32	10	7
Indonesia		1	
Kenya			2
Madagascar	1		
Malawi	1		
Mexico	4		
Mongolia			1
Nigeria	4		
Pakistan	1		
Philippines	1	4	
Republic of Korea		1	
South Africa	1		
Tanzania	1		
Thailand		5	1
Uruguay	1		
Uzbekistan	1		
Viet Nam		1	
Zambia	1		
Zimbabwe	5		1

The rates of SOC increase calculated in this study should be interpreted carefully. Recent research has demonstrated that comparing carbon stocks from two sites or treatments on the basis of samples taken to equal depth, rather than equal mass of soil (box 1), can overestimate rates of SOC increase by 20-30 per cent due to differences in bulk density (Palm et al. 2013, cited in Powlson et al. 2016). Of the 108 SOC studies in our dataset, only 22 measured increases in SOC stocks on the basis of equal soil mass rather than equal soil depth.

2.2 Analysis

The effect of agricultural practices on SOC stocks was calculated as the difference between SOC stocks in the "improved" and control treatments, divided by the duration of the experiment, multiplied by a factor for converting carbon to CO_2 (equation 1).

$$\textit{SOC stock change } (t\ CO_2\ ha^{-1}\ year^{-1}) = \frac{Cstock_{treatment} - Cstock_{control}}{\textit{experiment duration (years)}} \times \frac{44}{12} \tag{1}$$

Fertilizer-induced N_2O emissions were calculated by subtracting N_2O emissions in the unfertilized control treatment from N_2O emissions in the treatment with fertilizer application and dividing by the quantity of nitrogen applied, to standardize all experiments to a per-unit nitrogen emission factor. To then estimate the emissions likely with a "typical" development intervention, we multiplied all data points by a nitrogen application rate of 200 kg ha^{-1} $year^{-1}$ (0.2 t ha^{-1} $year^{-1}$), the median nitrogen application rate in the dataset. Finally, all data points were multiplied by the global warming potential of N_2O to convert to CO_2 equivalent emissions (equation 2).

$$N_2O \textit{ emissions from N fertilizer } (t\ CO_2\ e\ ha^{-1}\ year^{-1}) = \frac{N_2O_{fertilized} - N_2O_{unfertilized}}{\textit{N applied } (kg\ ha^{-1})} \times 200 \times 298 \times 0.001 \tag{2}$$

The effect of agricultural practices on CH_4 emissions from paddy rice was calculated as the difference between total seasonal emissions in the treatment and emissions in the control, divided by the duration of the season in days, to standardize all experiments to a daily emission factor. All data points were then multiplied by 120 days, the time to maturity for a medium-duration rice variety. Finally, all data points were multiplied by the global warming potential of CH_4 to convert to CO_2 equivalent emissions (equation 3).

$$CH_4 \textit{ emissions from rice } (t\ CO_2\ e\ ha^{-1}\ season^{-1}) = \frac{CH_{4\ treatment} - CH_{4\ control}}{\textit{experiment duration (days)}} \times 120 \times 25 \tag{3}$$

All studies were classified into climate zones according to the IPCC (2006) classification by overlaying the geo-referenced study location with a map of IPCC climate zones (figure 2).

The effects of improved practices on SOC and GHG emissions were analysed globally using the entire dataset and separately within each climate zone because climate has a significant effect on SOC stocks and GHG emissions. To calculate the overall mean effect of each agricultural practice on SOC stocks and GHG emissions, the effect size from each study was weighted by the number of replicates (n) from each study (equation 4).

$$Overall\ mean\ effect\ size = \frac{study\ effect\ size \times n}{\sum n} \qquad (4)$$

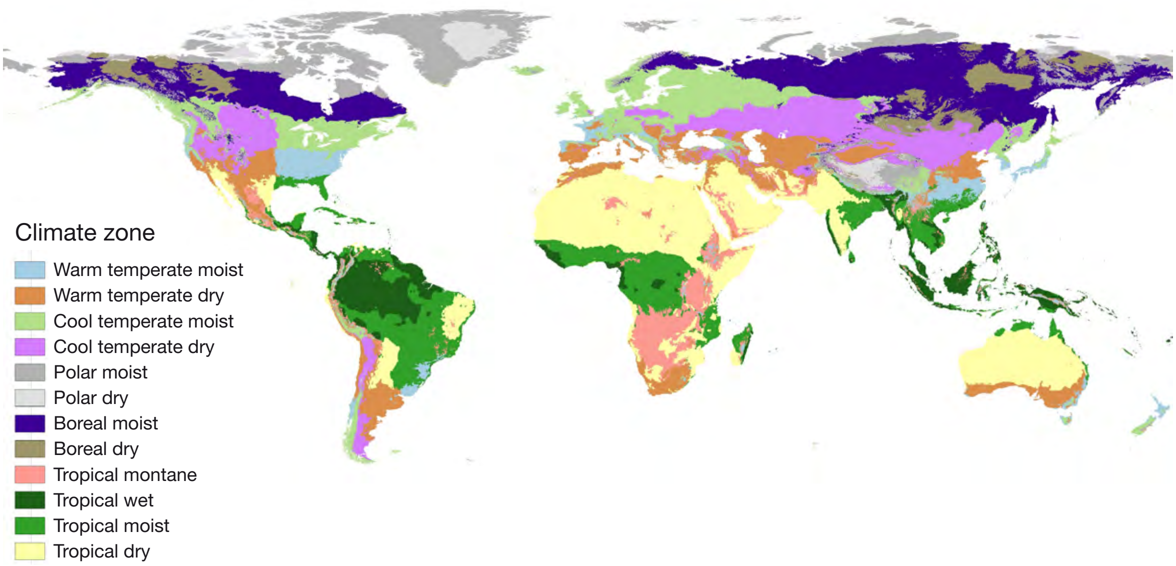
Within each climate zone and practice type, extreme outliers – defined as more than three times the interquartile range (IQR) outside the first or third quartiles – were removed (equation 5).

$$Extreme\ outlier = Q_1 - 3 \times IQR,\ or\ Q_3 + 3 \times IQR \qquad (5)$$

Due to incomplete reporting of standard deviations, we used the between-study variation to assess the overall levels of effects and variability. Confidence intervals for overall effects of agricultural practices on emissions and SOC stocks were calculated using the weighted variance (equation 6).

$$CI_{95} = 1.96 \times \frac{\sqrt{(\sum n[(study\ effect\ size - overall\ mean\ effect\ size)^2]/(\sum n)}}{\sqrt{\sum n}} \qquad (6)$$

Figure 2 IPCC climate zones



Classification is based on elevation, mean annual temperature, mean annual precipitation, ratio of mean annual precipitation to potential evapotranspiration, and frost occurrence. Data from the Joint Research Centre of the European Commission.

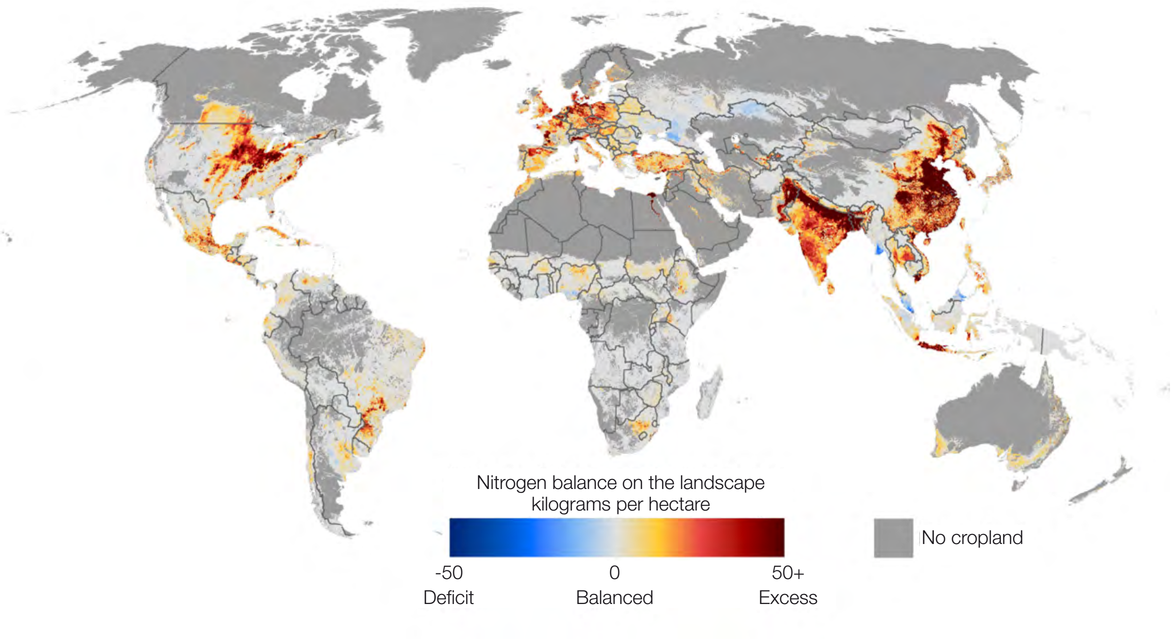
3 Results and discussion

3.1 Mitigation potential of improved agricultural practices

Practices that increased organic matter inputs to soil (crop residue management, organic fertilizers and agroforestry) had the largest mitigation potential through increases in SOC stocks, regardless of soil type (figure 4). Carbon inputs are the main driver of SOC stock changes in tropical croplands (Fujisaki et al. 2018). Reduced tillage (minimum or no tillage) without concurrent increases in organic matter inputs (such as from residue retention or cover crops) had smaller effects on SOC stocks. The change in SOC with the adoption of minimum tillage was not significantly different from zero. This is consistent with the literature on conservation agriculture and SOC, which has found that increases in SOC with reduced or no tillage are unlikely without additional organic matter inputs (Powlson et al. 2014; 2011; Richards et al. 2014). The full conservation agriculture package (no tillage combined with increased crop diversity and crop residue retention) had very high mitigation potential, though this was strongly influenced by a single study from Brazil (Sá et al. 2006). The effect of increased crop diversity alone was negligible (figure 4).

Use of nitrogen-containing fertilizer (either synthetic or organic, assuming an application rate of 200 kg N ha^{-1}) increased N_2O emissions by approximately 0.5 t CO_2e ha^{-1} $year^{-1}$ (figure 4). An application rate of 200 kg N ha^{-1} was representative of the dataset used in this study, but application rates in the context of IFAD-supported projects may be lower, leading to smaller emissions increases. In areas where nitrogen fertilizers are overused (figure 3), more efficient use of fertilizers represents a significant mitigation opportunity (Richards et al. 2016). In the context of food security and development interventions, however, introduction or increased use of fertilizers is more likely than a reduction in fertilizer use, so we analysed the data on N_2O emissions assuming that the change in agricultural practice would be an increase in nitrogen application, rather than a decrease. However, in our analysis, the mitigation potential of increased fertilizer applications – especially organic fertilizers – through SOC stock increases was greater than the global warming potential of increased N_2O emissions, even at relatively high application rates. A recent modelling study showed that SOC accumulation likely offsets the increased N_2O emissions associated with SOC-enhancing practices during the early years of a change in practice (which would be reflected by the short-term studies in the dataset used in this analysis). In the long term, however, N_2O emissions will eventually be larger than carbon accumulation, as SOC reaches equilibrium (Lugato et al. 2018). This increase in emissions will need to be further balanced against the food security benefits of potential production increases.

Figure 3 Nitrogen balance on the landscape



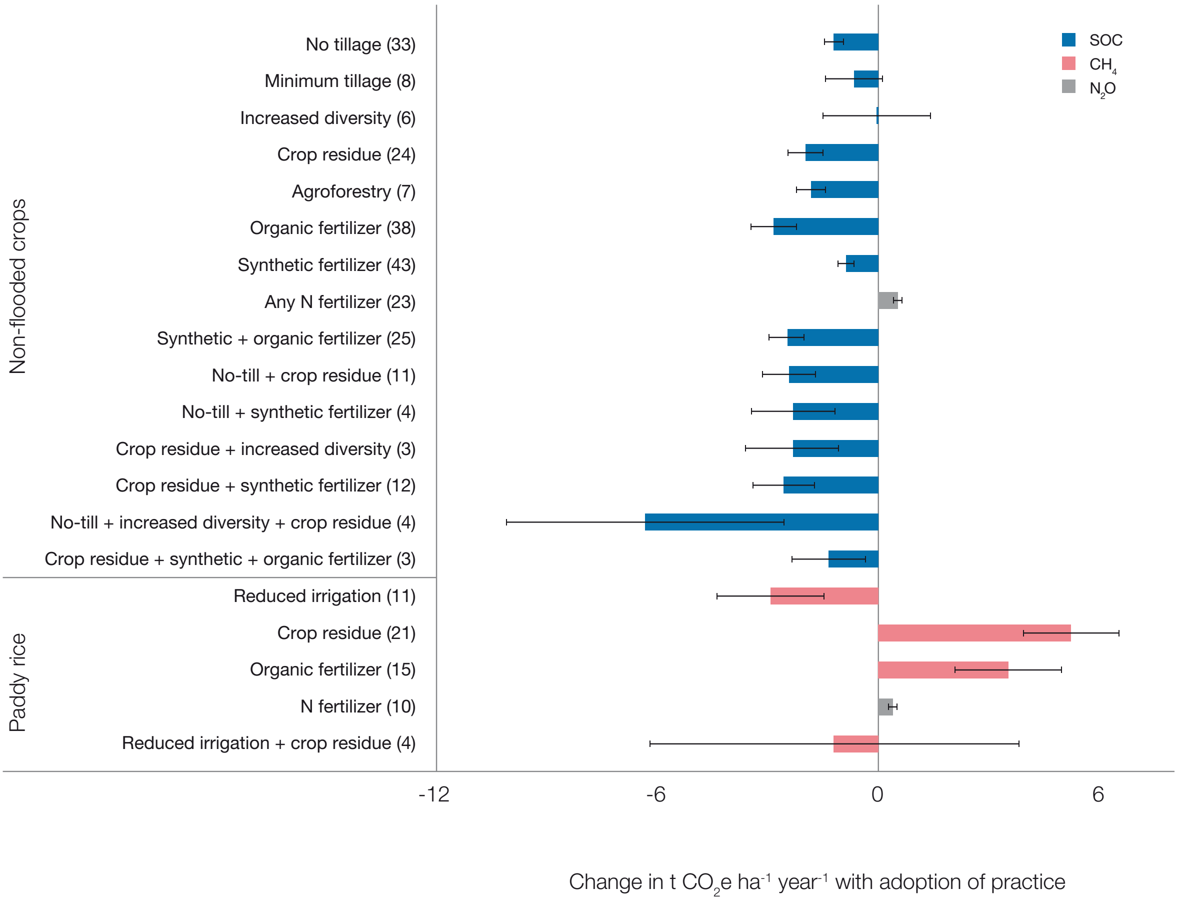
Source: Peder Engstrom and Paul West, Institute on the Environment, University of Minnesota; in Richards et al. (2015).

On a per-hectare basis, the mitigation potential of reduced irrigation for one season of a paddy rice crop was similar in magnitude to SOC-enhancing practices in non-flooded crops (figure 4). The mitigation potential could theoretically be even higher in sites where two or more seasons of rice are grown in a single year. In practice, however, mid-season drainage or alternate wetting and drying are only suitable during one (drier) cropping season in many rice-growing areas, due to high rainfall during the wet season (Sander et al. 2017).

The addition of crop residues and organic fertilizer to paddy rice increased CH_4 emissions by approximately 4-5 t CO_2e ha^{-1} year^{-1} on average. Management of crop residues and organic material also represents a mitigation opportunity. Composting residues and/or adding them to the field during the dry season when the field is not flooded can reduce CH_4 emissions relative to adding them during the cropping season (Tariq et al. 2017). Leaving rice straw on the soil surface before a non-flooded crop such as wheat also has potential to increase SOC, with minimal effect on CH_4 emissions. This analysis did not account for emissions from residue burning, which is a commonly practised alternative to incorporation or mulching of residues. Emissions from straw burning are likely less than those created by leaving residues in paddy fields, but burning also causes air pollution and human health hazards (Gaihre et al. 2014; Romasanta et al. 2017). Lower-emission uses for rice straw include collection and use in power generation, ethanol or biogas production, mushroom cultivation or as a soil amendment in non-flooded crops (Romasanta et al. 2017; Wang et al. 2016).

The combined effect of reduced irrigation and the application of crop residues on CH_4 emissions was highly variable among studies. This is not unexpected, as the two practices have opposing effects on CH_4 emissions, and the net effect depends on the quantity and timing of the residue addition, as well as the timing of paddy drainage (Tariq et al. 2017). Finally, as with non-flooded crops, nitrogen fertilizers caused a small net increase in GHG emissions, on average.

Figure 4 Mitigation potential of climate-smart practices



Negative values represent a reduction in GHG emissions (or carbon sequestration). Values in parentheses are the number of studies. Positive values represent an increase in GHG emissions, rather than mitigation. Authors' own calculations.

Box 2 Mitigation potentials in livestock systems

Though empirical data on the mitigation potential of livestock management practices in the tropics are scarce, modelling studies can provide an estimate of the likely mitigation potential of livestock development projects. Mitigation practices that increase animal productivity generally also increase emissions but decrease CH_4 per unit of animal product (emission intensity). Using a model of ruminant digestion, CH_4 emissions and productivity, Thornton and Herrero (2010) found that productivity-enhancing interventions in the tropics could reduce emission intensity in dairy systems by up to 0.9 t CO_2e t milk^{-1}.

Management practice	**Δ GHG emissions** (t CO_2e animal^{-1} yr^{-1})	**Δ yield** (t milk yr^{-1} animal^{-1})	**Δ emission intensity** (t CO_2e t milk^{-1})
Improved pasture (enteric CH_4)	0.2	0.8	-0.9
Improved cereal stover digestibility (enteric CH_4)	0.1	0.8 (177%)	-0.6
Grain supplementation (enteric CH_4)	0.1	1.3 (277%)	-0.8
Replacement of cereal stover with agroforestry fodder (enteric CH_4)	0.2	0.8	-0.5
Improved breeds (enteric CH_4)	0.7	1.4	0.1

Management practices in grazing-based systems also have mitigation potential via SOC sequestration. A recent meta-analysis (not limited to the tropics) found that improved management of existing grasslands can significantly increase SOC stocks (Conant et al., 2017).

Management practice	**Mitigation potential** (t CO_2e ha^{-1} yr^{-1})
Sowing legumes	2.4
Fertilization	2.1
Grazing management	1.0

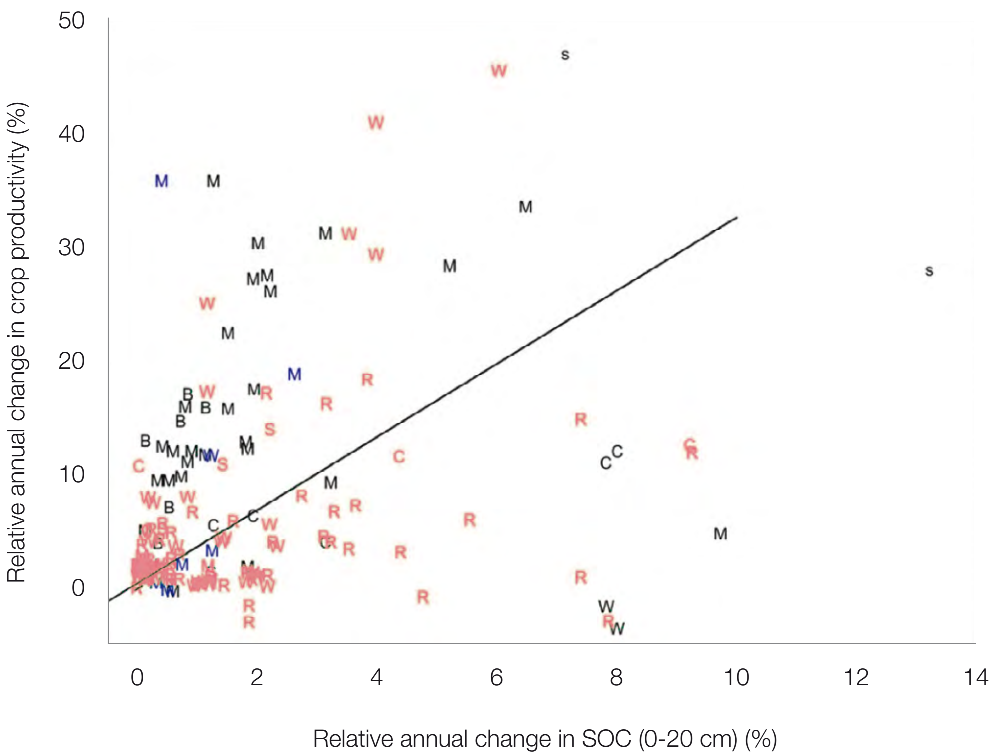
3.2 Yield impacts of improved agricultural practices

The dataset used in this study lacked comprehensive, co-located yield data. However, results from a subset of the data as well as from other studies provide some general guidance on which improved practices are likely to increase yields and mitigate climate change.

In general, increases in SOC are associated with increased crop yields (figure 5). Practices such as reduced tillage and crop residue retention have the potential to buffer crop yields against weather extremes, especially in drought-prone areas (Richards et al. 2014), as well as increase average yields in the long term. However, improvement of soil structure and fertility is a slow process; research on conservation agriculture has shown that farmers may need to wait three to seven years to experience yield increases (Richards et al. 2014). Moreover, improving soil structure and fertility to improve yields depends on sufficient biomass production by crops, or additions of organic material such as manure from off-field. In many cropping systems, especially in sub-Saharan Africa, the need for crop residues as livestock feed constrains the effective practice of mulching and other practices for improving soil fertility. Combining an appropriate use of fertilizers with residue mulching can increase crop yields and the available quantity of crop residues. Nitrogen inputs also help avoid yield penalties, as large carbon inputs to the soil in the form of mulch can promote nitrogen immobilization by micro-organisms, making it unavailable for crops.

Water-saving interventions in paddy rice have little effect on rice yields when practised properly (i.e. not allowing soil water levels to drop more than 15 cm below the soil surface) and can reduce water use by over 20 per cent (Carrijo et al. 2017). The primary benefit of such practices for the farmer is savings on fuel for water pump operation, or water itself where farmers pay per volume for irrigation water.

Figure 5 Relative annual changes in crop productivity and in SOC stock (over 0-20 cm) (%) after changes in land management improving SOC



The results correspond to a meta-analysis of 32 papers, reporting 151 relevant comparisons of location, practice and crops over four years or more. Crop species: B, beans; C, cassava; M, maize; P, sweet potatoes; R, rice; S, soybean; s, sorghum; W, wheat. Field experiment regions: Africa (black); Asia (green); Latin America (blue). The solid line is the Standard Major Axis regression for all data points (n=151, Spearman's rank correlation: y=0.495 + 3.21 x; r=0.205, P<0.012) (Soussana et al. 2017).

3.3 IFAD portfolio of investments in climate-smart agriculture

Over its ninth replenishment period (2011-2014), IFAD invested approximately US$5.6 billion in 189 projects to improve productivity, market participation and climate resilience. Using 90 project design documents, we identified projects that supported implementation or scale-out of improved agricultural practices that are also found in the Climate-Smart Agriculture Compendium as defined in table 1. The agricultural practices most commonly included in IFAD investments were irrigation and water harvesting, followed by reduced tillage, agroforestry, increased crop diversity, and organic fertilizers (table 3).

Extensive review criteria were developed to capture information needed to assess the emission potentials using the methodology presented above. Information required included details of agricultural practices promoted (e.g. tillage, manure management, residue management), combinations of practices promoted, and numbers of farmers and area targeted. This analysis relied on the information provided in project design documents captured in an existing extensive dataset, which generally do not include details about changes in field-level agricultural practices anticipated by the project or the precise geographical extent of anticipated impacts. Detailed ex post data on project activities and costs have also been screened for more detail, and the level of detail required for this analysis was similarly not enough. Given that this analysis focuses on ex ante mitigation potential, data in project design documents were deemed suitable for this project.

To estimate the total mitigation potential of IFAD investments in improved agricultural practices, we assumed that each farmer targeted for a particular project intervention adopted the improved practice on 0.5 hectares of land, based on recent estimates that 72 per cent of farms worldwide are less than 1 hectare (Lowder et al. 2016). We further assumed that practices would be maintained indefinitely without dis-adoption and that all the farmers and hectares targeted for adoption were unique (e.g. none of the farmers adopting agroforestry were the same farmers also adopting organic fertilizer). These assumptions are part of the reason why our findings represent an upper bound.

Using the global mean mitigation potentials calculated in this analysis, we estimated a total annual mitigation potential for field-level practices within the IFAD9 portfolio of between 738,000 and 1,740,000 t CO_2e year^{-1}. The lower and upper bounds reflect the 95 per cent confidence intervals of the mitigation potentials. This is approximately equivalent to removing between 158,000 and 372,500 passenger vehicles from the road for one year. Agroforestry made the largest contribution to this mitigation potential because of the potential to sequester carbon in both soil and biomass, despite a smaller number of farmers targeted by investments with this practice than others such as increased crop diversity.

Irrigation and water harvesting infrastructure comprised nearly 45 per cent (US$1,592 million) of IFAD investments in practices included in this analysis. Construction or improvement of irrigation systems does not have intrinsic mitigation potential, but it can enable practices that increase SOC or reduce GHG emissions. While not represented in the dataset used in this analysis due to the sparseness of data from developing countries, irrigation does have potential to increase SOC by increasing plant growth and associated returns of organic residues to the soil. However, the influence of irrigation is highly dependent on climate, initial SOC content, and management factors such as tillage and crop residue management (Trost et al. 2013). In general, irrigation has the greatest potential to increase SOC where initial SOC is low – for example, in cultivated desert soils (potential increases of between 90 and 500 per cent) and soils in semi-arid regions (potential increases of between 11 and 35 per cent) (Trost et al. 2013).

Improvements in irrigation infrastructure can enable mitigation of CH_4 emissions through more efficient water management in paddy rice. Practices such as alternate wetting and drying require proper infrastructure to allow drainage of irrigation water and reliable water supply for re-flooding. Such water-saving and CH_4-reducing irrigation practices are less

Table 3 Improved agricultural practices within IFAD's investment portfolio during IFAD9 period (2011-2014), as determined from project design documents, and their estimated annual mitigation potential at the portfolio level

Practices promoted	IFAD contribution (US$ million)	Number of projects	Farmers targeted (000)	Effect on GHG emissions	
				Per hectare (t CO_2e ha^{-1} year^{-1})	Total for IFAD portfolio (thousand t CO_2e year^{-1})
Pasture management[a]	48	3	50	-2.10 (soil C) 0.54 (N_2O)	-60 – -25 10–16
Reduced irrigation of paddy rice	67	2	34	-2.94 ± 0.08	-75 – -25
Live fences[b]	72	3	20	-1.83 ± 0.40 (soil C) -2.13 ± 0.70 (biomass C)[g]	-22 – -14
System of rice intensification[c]	75	4	21	-2.94 ± 1.47	- 46 – -15
Synthetic fertilizer	86	1	120	-0.88 ± 0.22 (soil C) 0.54 ± 0.12 (N_2O)	- 66 – - 40 25–39
Crop residue management[d]	89	5	15	-1.98 ± 0.48	-18 – -11
Green manure[e]	98	3	47	-1.98 ± 0.48	-58 – -35
Organic fertilizer	205	5	135	-2.86 ± 0.62 (soil C) 0.54 ± 0.12 (N_2O)	-235 – -151 28–44
Biogas	243	5	181	No data	No data
Increased diversity of crops	253	9	167	-0.04 ± 1.47	-126–119
Agroforestry	293	8	124	-1.83 ± 0.40 (soil C) -10.82 ± 2.57 (biomass C)[h]	-139 – -89 -829 – -511
Minimum/no till[f]	430	11	187	-0.66 ± 0.77	-137 – -10
Water harvesting	527	12	400	No data	No data
Irrigation	1 065	33	392	No data	No data

Negative values represent a reduction in GHG emissions (or SOC sequestration). Positive values represent an increase in GHG emissions. Practices are shown in increasing order of IFAD contributions.

[a] Assumes fertilization of pasture (box 2), from Conant et al. (2017); does not include potential changes in enteric CH_4.

[b] Mitigation potential of agroforestry was used for soil carbon.

[c] Mitigation potential of reduced irrigation of paddy rice was used.

[d] Mitigation potential of crop residue management was used.

[e] Includes investments in pasture improvement and animal husbandry.

[f] Mitigation potential of minimum tillage used to provide a conservative estimate.

[g] Biomass carbon sequestration potential from Cardinael et al. (2018) for hedgerows in tropical climates.

[h] Biomass carbon sequestration potential from Cardinael et al. (2018) for shaded perennials in tropical climates.

effective (or even impossible) without effective control over irrigation water (Tariq et al. 2017). Conversely, if rice is not currently grown under flooded conditions, implementation of irrigation can increase CH_4 emissions.

Pasture management can also alter enteric CH_4 emissions from livestock by improving the quality or availability of fodder. Improved pasture generally increases emissions per animal but increases productivity such that emissions per unit of meat or milk production (emissions intensity) decrease. Decreases in emissions intensity can lead to decreases in absolute emissions if they are accompanied by a reduction in the size of the herd. This analysis did not attempt to extrapolate changes in animal numbers to estimate mitigation of enteric CH_4 via pasture management. Such projections, or at least an estimate of current herd size, would be an important variable to understand changes in enteric CH_4 emissions resulting from IFAD investments in livestock value chains.

IFAD9 also invested US$243 million in biogas systems. However, there was insufficient literature to include biogas in the dataset used for this analysis. Biogas digesters – also called manure digesters, methane digesters or anaerobic digesters – are closed systems that anaerobically digest waste (manure, food waste or sewage), producing biogas and a nutrient-rich slurry that can be used as fertilizer. The biogas produced is primarily CH_4 and may be captured and flared or used as fuel. Biogas digesters, therefore, have the potential to reduce GHG emissions from poorly managed manure, as well as avoid emissions from fossil fuel use or tree removal for firewood. The mitigation potential of biogas digesters as a manure management strategy is highly variable; CH_4 conversion factors (indicating the proportion of CH_4-reducing potential achieved for a manure management system) range from 0 to 100 per cent (IPCC 2006).

4 Conclusions

4.1 Relative contribution of practices to the climate change mitigation potential of the IFAD portfolio

The majority of the GHG mitigation potential resulting from IFAD investments was in carbon sequestration (figure 6) in biomass and soil. The use of organic fertilizers and agroforestry contributed the most to the total mitigation potential of the portfolio. Minimum tillage also made a large contribution due to the number of projects that included this practice, despite its comparatively small mitigation potential. Water-saving irrigation practices such as alternate wetting and drying in paddy rice have per-hectare mitigation potentials similar to those of the SOC-enhancing practices evaluated, but their contribution to the total mitigation potential of the portfolio was smaller due to the smaller number of projects that included such practices.

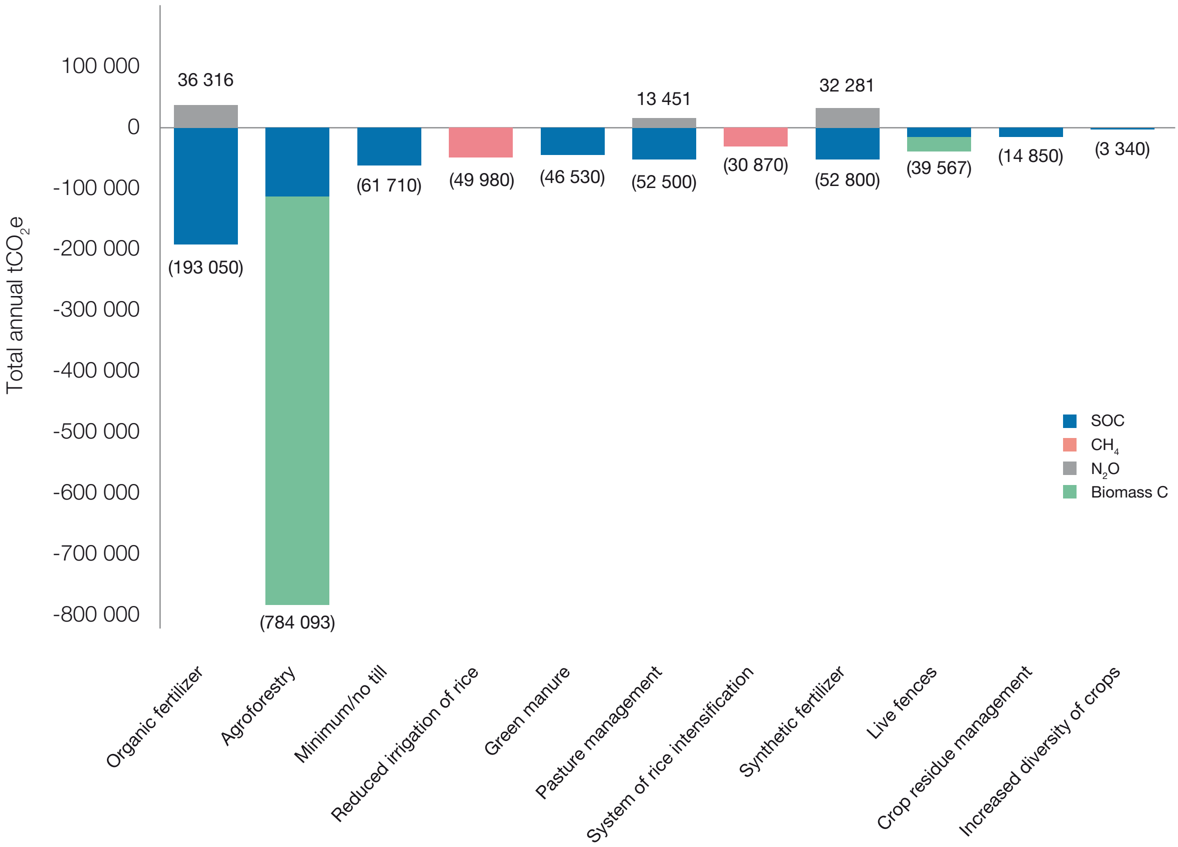
Investments in irrigation infrastructure comprised 30 per cent of the IFAD portfolio but have limited mitigation potential in and of themselves. Irrigation does have the potential to facilitate agricultural practices with mitigation potential, such as increasing biomass inputs to soil (as crop residues) or enabling more efficient use of water in paddy rice. However, flood irrigation can also increase CH_4 emissions if introduced where it was not previously practised.

The use of fertilizer has the potential to mitigate climate change through SOC sequestration and to increase GHG emissions. A net mitigation effect – demonstrated in this analysis – is more likely in the short term, but this may be outweighed by increased N_2O emissions in the long term. Increased emissions may be minimized by supporting practices and policies that promote high nitrogen use efficiency, such as adaptive nutrient management, balanced nutrient inputs, and optimal use of organic resources and high-yielding germ plasm (Richards et al. 2016).

4.2 Uncertainties and gaps in understanding mitigation potential

While a large part of the mitigation **potential** of the practices promoted in the IFAD9 portfolio covered in this study is due to SOC, the uncertainties involved in estimating SOC sequestration (box 1) make it difficult to predict when a particular project will **in fact** sequester carbon from the atmosphere, when it will simply slow SOC loss, and when it will have no effect on SOC whatsoever. Uncertainties for the emission factors calculated in this study ranged from 5 to 32 per cent (not including increased crop diversity, where uncertainty exceeded 100 per cent). The possible discontinuation of carbon-enhancing practices after project completion adds a further layer of uncertainty.

Figure 6 Total effect on GHG emissions of improved agricultural practices within IFAD's investment portfolio during the IFAD9 period (2011-2014)



Negative values represent a reduction in GHG emissions (or carbon sequestration). Positive values represent an increase in GHG emissions.

As a general rule, genuine increases in SOC stocks should not be expected unless a substantial increase in organic matter inputs (such as crop residues, manure or other biomass) combined with a reduction in soil disturbance (tillage and/or erosion) are expected results of the project. Reduced tillage or crop diversification alone is unlikely to sequester carbon. Even when a project predicts a change in crop residue management, the net impact of such a change on SOC stocks may be small if crop yields are too low to contribute significant biomass to the soil. Research on conservation agriculture in sub-Saharan Africa has shown that low biomass production results in limited SOC increases (Cheesman et al. 2016). This may have also contributed (among other constraints) to the low adoption and high dis-adoption rates of the practice despite large-scale promotion efforts by donors and governments (Giller et al. 2009; Nkala et al. 2011; Arslan et al. 2014). For other soil management practices not considered here, the Soil Best Bets compendium of CIAT[1] or the WOCAT Database on Sustainable Land Management[2] can provide a snapshot of likely SOC and other ecological benefits.

The mitigation potential of livestock-related interventions was a key gap in this analysis. Modelling studies have shown that productivity-enhancing practices tend to decrease

1. http://soilsbestbets.ciat.cgiar.org.
2. www.wocat.net/en/global-slm-database.

emissions per unit of meat or milk but increase emissions per animal. Therefore, such interventions are unlikely to reduce GHG emissions in the absolute sense unless coupled with reductions in herd size. In the long term, there is a critical need for more empirical data on the net GHG effects of improved livestock management practices. Including estimates of herd size and potential changes in herd size in project design documents could allow for at least a rough ex ante estimation of the GHG impacts of investments in livestock value chains.

Irrigation and biogas are also areas where IFAD makes significant investments, but this analysis was limited by a lack of empirical data on the potential for these investments to mitigate agricultural emissions. Irrigation has the potential to increase or decrease emissions depending on where and how it is implemented. Biogas may have significant mitigation potential as a manure management strategy, depending on the characteristics of the system. These technologies also interact strongly with energy systems, and their overall mitigation potential is determined by the energy sources used or replaced by their implementation. A full assessment of their mitigation potential should also account for energy-related emissions.

4.3 Improving ex ante evaluation of mitigation benefits

Estimating the mitigation potential of a project requires two pieces of information: activity data (information describing the change in agricultural practice that is expected to take place) and an emission factor (the net change in emissions expected from the change in practice, which we have calculated using empirical data in this analysis). Reducing the uncertainty of the mitigation potential of a given intervention can be done by using more accurate and precise activity data, a better emission factor, or both. While this study considered the uncertainty associated with emission factors, the uncertainty associated with the activity data – the information interpreted from project design documents – is perhaps even greater. It is difficult to predict exactly what will happen at the field level during the course of a project or after project completion, but a few key questions that can be asked during project design could help provide a better idea of whether a project may increase or decrease net GHG emissions. For example:

- Will this project result in a substantial increase in organic matter inputs to the soil and/or reduce carbon losses (e.g. through erosion or degradation)?
- For irrigation infrastructure projects in rice-producing areas: Will this project be accompanied by policy changes or farmer education to increase water use efficiency? Will it introduce flood irrigation in an area that has not been irrigated?
- For projects supporting increased access to fertilizers: What is the recommended rate of nitrogen fertilizer promoted by the project?
- For livestock projects: Will this project lead to an increase or decrease in herd size? How will the management of manure change?

However, a robust and transparent assessment of climate change mitigation by IFAD investments would require ex post analysis by incorporating mitigation objectives into the project monitoring system so that baselines are documented and data collected throughout the lifespan of a project. This can be done without dramatically increasing monitoring burdens. As during project design phase, data collection during implementation should focus on the practices likely to have the largest impact on emissions or carbon sequestration. Project design teams could identify these practices during the design phase, based on mitigation potentials presented here or through the use of an agricultural GHG calculator such as the Ex-Ante Carbon-balance Tool (Bernoux et al. 2010) or the Mitigation Options Tool (Feliciano et al. 2017), and then monitor the adoption of these focus practices. Monitoring during and post implementation should also serve the purpose of evaluating the accuracy of assumptions made during project design and ex ante assessment, to adjust those assumptions in future assessments of project mitigation potential.

Improving the estimation of SOC sequestration potential should be a priority given its relative contribution to the mitigation potential of IFAD investments. Careful collection of activity data and awareness of how ex ante assumptions can influence mitigation assessments can help improve accuracy in the short term. In the long term, there is a need for tools that link existing, spatially explicit data on soil and climate characteristics (available through programs such as ISRIC-World Soil Information) with advanced models of soil carbon dynamics. Such tools are currently available at the national level in countries such as the United States and Canada, but not yet at the global scale.

Ideally, monitoring of project-level mitigation impacts should also be methodologically consistent with countries' national systems for Measurement, Reporting and Verification (MRV) of GHG emissions and mitigation actions. As countries implement their NDCs, many are seeking to capture the effects of subnational projects and local mitigation actions in their national GHG inventories. In practice, there is often a mismatch between national and project-level MRV in terms of the datasets used, protocols for collecting and sharing data, and people and institutions involved. However, some countries such as Colombia are developing data management systems to harmonize the bottom-up approaches used by projects and the top-down approaches used to prepare national inventories (Valenta et al. 2018). While recognizing the need for consistency across IFAD investments, IFAD project design teams aiming to complement national initiatives may consider consulting with GHG inventory preparation teams to understand the methods and indicators that are used for national MRV and make use of existing data collection efforts.

To conclude, it is also important to highlight that all the practices taken into account in this analysis have been promoted and supported with the main purpose of helping farmers maintain or increase production through sustainable approaches and, therefore, adapting to climate change while at the same time achieving mitigation purposes.

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