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Agricultural development addresses food loss and waste while reducing greenhouse gas emissions

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Agricultural development addresses food loss and waste while reducing greenhouse gas emissions

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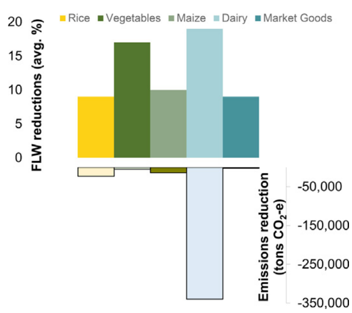
HIGHLIGHTS

- We studied 13 international development projects addressing Food Loss and Waste (FLW).
- A wide variety of interventions achieved substantial reductions in FLW.
- Greenhouse gas emissions per unit production decreased for many food products.
- Targeting FLW may also lower greenhouse gas emissions from food production.
- Reduced FLW and lowered emissions could be a win-win for international development.

GRAPHICAL ABSTRACT



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ABSTRACT

Food loss and waste (FLW) reduce food available for consumption and increase the environmental burden of production. Reducing FLW increases agricultural and value-chain productivity and may reduce greenhouse gas emissions associated with feeding the global population. Although studies of interventions that reduce FLW exist, almost no research systematically investigates FLW interventions across multiple value chains or countries, most likely due to challenges in collecting and synthesizing data and estimates, let alone estimating greenhouse gas emissions. Our research team investigated changes in FLW in projects supported by the United States Agency for International Development's (USAID) global hunger and food security initiative, Feed the Future. This was a unique opportunity to conduct ex-ante estimates of the impacts of FLW interventions across 20 value chains in 12 countries, based on project documents and interviews with USAID and project staff. This paper describes specific interventions in each value chain and country context, providing insight to interventions that decrease FLW at multiple points along food value chains, from upstream producer-dominated stages to downstream consumer-dominated stages. Amongst the sub-sectors studied, FLW interventions directed at extensive dairy systems could decrease FLW by 4–10%, providing meaningful greenhouse gas mitigation, since these systems are both

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emission-intensive and experience high FLW. More modest emissions reductions were found for other key agricultural products, including maize, rice, vegetables, fruits and market goods.

1. Introduction

One-third of food produced is lost or wasted globally (Gustavsson et al., 2011). Food loss and waste (FLW) forfeits time, effort, energy, and resources by decreasing food supply as products move from production towards consumption (Fig. 1), reducing effective yield, and leaving less food available for consumption (Fig. 1). In developing countries, food loss—food that is spoiled, spilled or otherwise lost before reaching the consumer—is much more common than food waste, which refers to discarding of food that is otherwise fit for consumption (HLPE, 2014; Kiff et al., 2016). Globally, the majority of FLW occurs during early stages of the value chain, including production (e.g., input choice), harvesting and storage (Porter and Reay, 2015; Sims et al., 2015), most often due to inadequate infrastructure and limited capital for investment (Beddington et al., 2012, Hodges et al., 2011, Rosegrant et al., 2016). Losses at each stage impact the next, cumulatively reducing the food available for retail and consumption (Fig. 1), giving a natural motive for all stakeholders to minimize loss FLW (Sheahan and Barrett, 2016).

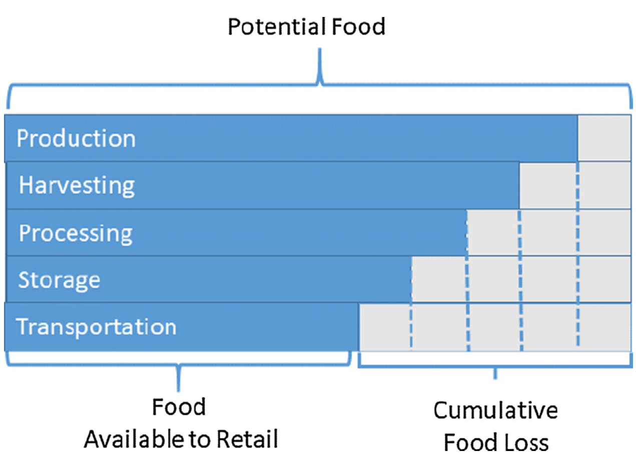

Fig. 1. Cumulative effects of FLW in the food value chain.Food available for retail distribution is the potential food minus the cumulative effects of food loss at each stage of the value chain. Losses vary by product and value chain stage.

Interventions at several different points on the supply chain can reduce FLW (Figs. 1, 2: production, harvest, processing, storage, and transport) although the relative portions of FLW at each stage may vary by food or local context. At the production stage, choices around agricultural inputs, such as seed and animal breed, can reduce FLW in later stages (HLPE, 2014). For example, producers may select seed varieties that produce goods with a longer shelf life (Pessu et al., 2011; Prusky, 2011), generate marketable products even under unfavorable conditions (e.g. drought-tolerant seeds), or maintain desirable food qualities (HLPE, 2014). In animal production, well-planned breeding and genetic considerations can lead to less incidence of disease or malformations (Stear et al., 2001).

Interventions to reduce FLW at harvest create emission reductions if they increase effective yield. Carefully designed crop calendars can help farmers time harvest to maximize shelf life (Prusky, 2011; Paulsen et al., 2015), for example farmers can use ambient conditions to dry grains before harvest. Educational seminars with

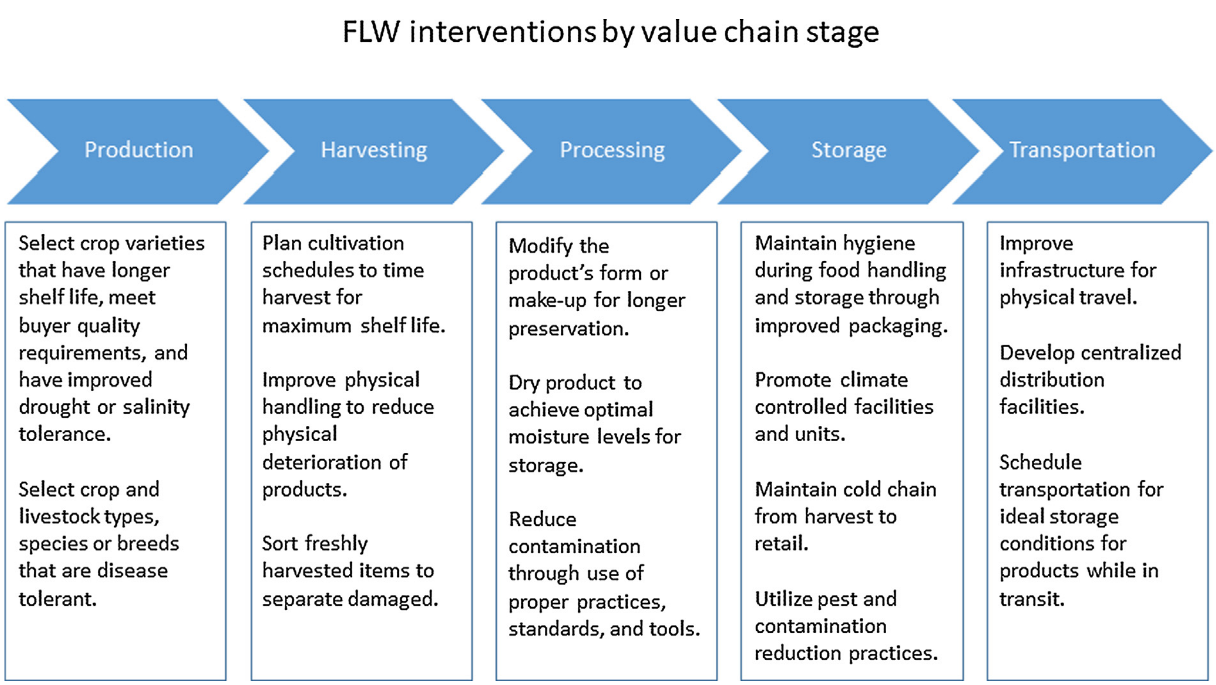

Fig. 2. Examples of FLW interventions at five stages in the food value chain.

topics such as operating mechanized equipment and physical handling of produce during harvest, reduces damage and deterioration of produce (Prusky, 2011, Paulsen et al., 2015). Improved training in milk handling practices of dairy farmers has been shown to reduce product contamination and microbial spoilage (Lore et al., 2005). Humidity gauges indicate optimal moisture levels for produce at harvesting time, reducing incidence of mold and rot (Hell et al., 2010).

Processing transforms a product into a longer-lasting form (Lore et al., 2005). Making butter from milk and drying fresh produce (Hell et al., 2010) are well-known mechanisms that reduce spoilage and preserve food stocks, resulting in greater effective yield and lower GHG emissions per unit of production (emission intensity). Processing interventions for staple crops such as rice and beans include proper drying in preparation for storage (Rani et al., 2013). Proper training in milk hygiene for food handlers reduces contamination (Karlovsky et al., 2016) and avoids spoilage (Lore et al., 2005).

Once harvested and processed, the storage location and physical microenvironment greatly influence FLW and thus emission intensity. Some physical containers (e.g., plastic crates, silos, triple bags) reduce FLW by limiting contamination, product deterioration, and predation by pests (De Groote et al., 2013; Lipinski et al., 2013; Baoua et al., 2014). Maintenance of the cold chain from harvest to retail or consumption also reduces spoilage (Prusky, 2011). Storage conditions, particularly efficient refrigeration and cooling structures for dairy and meat products (Lore et al., 2005) are limited and pose a challenge for food security and nutrition in many parts of the world. Innovative cooling mechanisms for food storage, such as low- to no-energy refrigerators, may aid in development initiatives (Lipinski et al., 2013). Packaging, which is included in storage in this analysis, plays a role in maintaining product quality through storage and shipment to retail (Opara and Mditshwa, 2013). Proper packaging can also improve hygiene and promote longer shelf life (Opara and Mditshwa, 2013).

FLW in transportation between harvest and retail can be reduced through infrastructure improvements, such as feeder roads that connect markets and agricultural centers (Beddington et al., 2012; KC et al., 2016), and collection centers (Lore et al., 2005). A collection center is a centralized hub where processors can pick up products or where commodities can be consolidated before retail. Transportation strategies, such as hauling during the cool part of the day, can also reduce losses (Pessu et al., 2011).

Reducing FLW in developing countries has the potential to increase food security by improving the availability of food for consumption and increasing household income from market goods (Stathers et al., 2013). Reducing FLW also has the potential to constrain unintended environmental impacts from food production (Hiç et al., 2016; Munesue et al., 2014), such as greenhouse gas (GHG) emissions from agriculture, which account for 10–12% of anthropogenic GHG emissions (Smith et al., 2014). In particular, reducing FLW reduces emission intensity, or the emissions per unit of product with benefits to mitigating climate change. For these reasons, halving food loss and waste by 2030 is amongst the strategies promoted by the United Nations Sustainable Development Goals (SDGs) (UN, 2015) to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture" and Paul Hawken (2017) prioritized FLW reduction as third most critical of 100 top strategies for reducing GHG emissions.

The importance of reducing FLW to climate change is widely recognized, but the literature on how FLW reductions impact GHG emissions is sparse, particularly in developing countries (Porter et al., 2016). In a review of scientific literature assessing FLW as a climate change mitigation strategy, Nash et al. (2017) found 23 studies addressing GHG emissions related to FLW, including only one that presented primary data on FLW for specific crops in a specific location (Goldsmith et al., 2015); the other 22 papers relied on pre-existing studies or data for regional to global estimates. Parfitt et al. (2010) identified quantification of FLW and potential reduction methods as a significant challenge and knowledge gap. Some literature has begun to address this knowledge gap, including embedded GHG emissions from global FLW (Porter et al., 2016), food waste for typical foods consumed in Switzerland (Beretta et al., 2017), life cycle analysis of vegetable supply chains

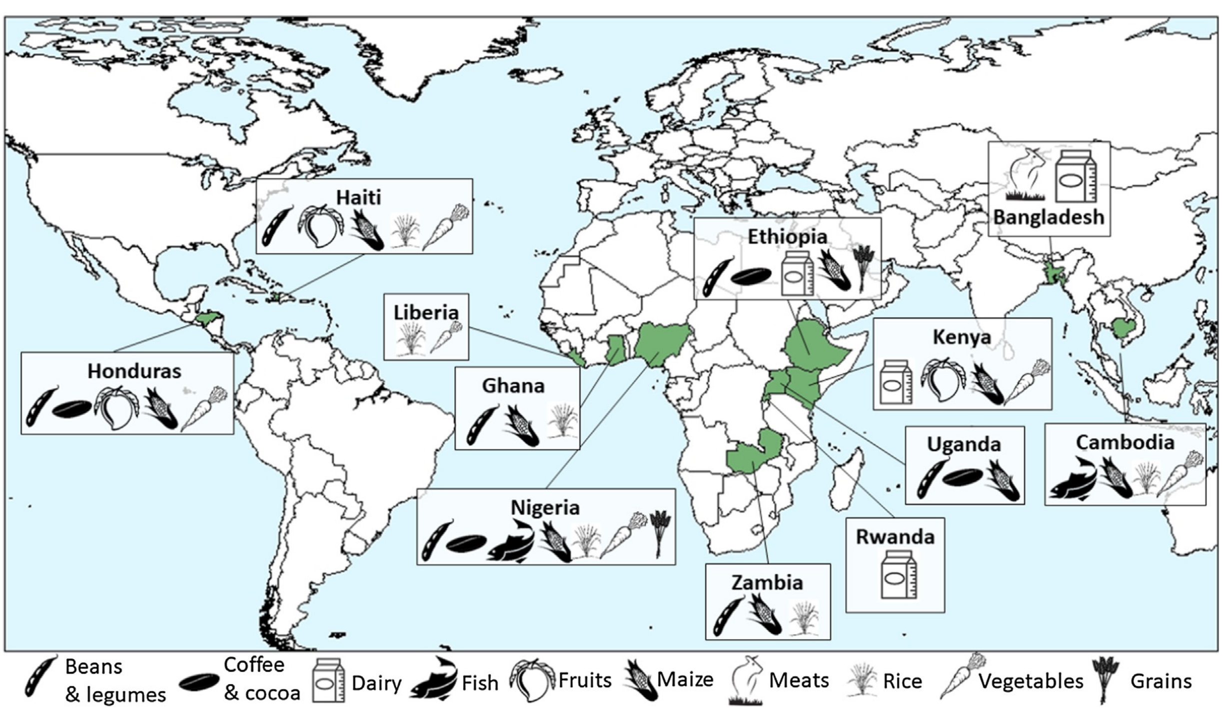

Fig. 3. Feed the Future projects reporting reductions in FLW by agricultural product.

in Japan (Wakiyama et al., 2019) and GHG emissions for U.S diets and related food loss (Heller and Keoleian, 2015). For developing world contexts, this knowledge gap largely remains unanswered. This study is unique in addressing this gap by considering 1) a range of developing country settings, 2) a wide variety of foods, 3) the food security context for food loss and 4) the use of local data on FLW. We analyzed 13 agricultural development projects from the United States Agency for International Development (USAID) Feed the Future (FtF) to examine specific FLW interventions and estimate their impacts on GHG emissions and emission reductions.

2. Methods

This research builds on Grewer et al. (2018), which estimated the climate change mitigation potential of 26 FtF projects and is the source of GHG estimates used here. As a team with Grewer et al. (2018), we conducted semi-structured interviews and standardized review of project documentation (e.g., monitoring and evaluation data, reports, project descriptions). Activities identified in FtF projects that affected agricultural emissions either positively or negatively included interventions in management of cropland (improved soil management, reduced crop residue burning, improved water management, increased organic matter application, increased/decreased fertilizer application, increased pesticide application), of livestock (reduced/increased herd size, increased feed quantity, improved breeding), of flooded rice (alternative wetting and drying, reduced rice maturity duration, fertilizer deep placement), agroforestry (increased biomass, increased soil carbon, land use change), of grassland and forests (land rehabilitation, avoided burning/degradation/conversion, reforestation/afforestation) or of other categories (establishment of irrigation, reduced fuel consumption) (Grewer et al. 2018).

Here, we focused on the impacts of FLW interventions, which are typically implemented in "bundles" with several interventions enacted across different phases of the value chain. We selected thirteen projects that engaged in FLW-reduction interventions, implemented in 12 countries in Africa, Asia, Latin America, and the Caribbean and in a range of food systems (Fig. 3). In Fig. 3, beans and legumes include soybean, chickpeas, groundnuts; dairy includes camel and cow; fruits include mango, and passionfruit; vegetables includes bitter gourd, cassava, cucumber, eggplant, longbean, potato, plantains; grains include wheat, sorghum and sesame. We included interventions at the pre-harvest management, harvesting, processing, storage, and transportation stages of the food supply chain that were carried out by input suppliers, producers, and processors. We reviewed potential pathways of emission reduction relative to food production in each case. In this paper, we used a bookkeeping model to estimate changes in FLW from baseline levels and resulting impacts of FLW-reduction activities on GHG emissions.

2.1. Project selection

From a preliminary desk review, we found 150 FtF projects had potential effects on net GHG emissions. Of this, 26 were analyzed for net impacts on GHG emissions (Grewer et al. 2018). All projects were active for 3 to 5 years at the time of this assessment, which meant we could work with a range of project data sets and affiliated individuals. We engaged with teams and individuals in the USAID FtF program (headquartered in DC), USAID country missions (in-country headquarters for all USAID projects), and USAID implementing partners (e.g., contractors running a specific project) to select projects related to FLW for this study. Generally, we engaged with project managers within the implementing partner organization who were experts with significant experience working in the targeted value chains and in the context of that country. We examined 26 FtF projects that aimed to boost farmer food security and nutrition with interventions that were studied for their net GHG emissions (Grewer et al. 2018). Through questionnaires and interviews with 19 FtF country missions, we identified projects with strong monitoring and evaluation programs and timelines sufficient to document projects' FLW impacts. We narrowed the analyses to a set of 13 projects (Table 1) that documented FLW in robust monitoring and evaluation systems (e.g., targeted, standardized,

Table 1
Analyzed projects studied span 12 countries and a wide range of products with FLW interventions.

Country, Project name	Agricultural products with potential for reduced FLW
Bangladesh Livestock for Improved Nutrition (LPIN)	Dairy, meat
Cambodia, Helping Address Rural Vulnerabilities and Ecosystem Stability (HARVEST)	Fish, rice, vegetables
Ethiopia, Agricultural Growth Program —Ag and Market (AGP-AMDe)	Coffee, maize, sesame, wheat, legumes (chickpea)
Ethiopia, Camel Milk Project (Camel Milk)	Dairy
Ghana, Agricultural Development and Value Chain Enhancement II (ADVANCE II)	Maize, rice, legumes (soybeans)
Haiti, Chanje Lavi Plantè (Chanje)	Legumes (beans), vegetables (plantain), maize, fruit (mangos), rice
Honduras, ACCESO (ACCESO)	Maize, plantain, legumes (beans), vegetables (onions, potatoes), fruit (passion fruit)
Kenya, Kenya Agriculture Value Chains Program (KAVES)	Dairy, maize, fruit (passion fruit, mangos)
Liberia, Food and Enterprise Development (FED)	Rice, vegetables
Nigeria, Maximizing Agricultural Revenue and Key Enterprises in Targeted States II (MARKETS II)	Fish, vegetables (cassava), rice, cocoa, sorghum, maize, legumes (soybeans)
Rwanda, Rwanda Dairy Competitiveness Project (RDCP)	Dairy
Uganda, Commodity Production and Marketing (CPM)	Legumes (beans), coffee, maize
Zambia, Better Life Alliance (BLA)	Legumes (soybeans and groundnuts), maize, rice

computer-assisted survey with farmers to quantify FLW changes related to project activities). The bundles of interventions promoted by each the 13 projects targeted multiple crop and livestock products (Fig. 3). FLW interventions were most common for maize and rice, though one project, MARKETS II, included FLW interventions for six commodities. Examples of interventions by commodity can be found in Appendix A.

2.2. Data collection

Our team collected and reviewed various forms of documentation from each FtF project, as there was no central repository for the needed details for this analysis, in the following steps: 1) reviewed project documentation, 2) conducted questionnaire with implementing organization, 3) held semi-structured interviews with implementing organization, and 4) followed-up on details as needed with implementing organizations.

Engagement with project implementing partners was crucial to collecting data on FLW, as it provided access to reports, data sets and staff for interviews. Documentation included project design documentation (binding plans used in selection by USAID), reports on monitoring and project updates (e.g., newsletters, quarterly reports required by USAID as part of the monitoring and reporting system), and project websites. Additionally, data on project activities needed for GHG estimates (e.g., practices, area of implementation, yields) and FLW estimates (e.g., interventions, yields, food loss rates) was provided by implementing partners from monitoring and evaluation activities in questionnaires and interviews, as well as extracted from previously aggregated (project-level) information found in project documentation and verified with disaggregated (raw) data shared by implementing partners' staff or project managers.

For FLW, implementing partners provided estimates of FLW with and without project interventions and described FLW interventions, along with additional data on adoption rates of improved agricultural practices and annual yields. USAID, as does the United Nations Food and Agriculture Organization, defines food losses as occurring from field to market (HLPE, 2014), and interviewees emphasized this definition of food loss, which includes production (harvest and input selection), processing, and storage losses. Projects collected data on yields as part of their monitoring and evaluation systems. It should be noted that recording yield and losses of dairy products was required, but dairy estimates are subject to greater uncertainty due to movement of producers and product in sometimes diffuse ways, which can limit accuracy.

We reviewed and coded project documents, including work plans, websites, and annual and quarterly monitoring reports. This content analysis yielded information on the breadth of FLW interventions and enabled identification of key terms for interventions based on phases. For example "threshing" was coded as a processing intervention, and "covered silo" was coded as a storage intervention. Many projects promoted multiple interventions to reduce losses of a single product, a "bundle" of practices jointly targeting FLW. In these cases we analyzed the aggregated impact of the interventions on FLW.

2.3. Estimating mitigation potential of FLW interventions

Using records of yields and FLW before and after project implementation, we estimated the GHG impacts of food production in both the business-as-usual (BAU, before project implementation) and with-project scenarios. We estimated GHG emissions and carbon sequestration associated with both business-as-usual and with project interventions using the Ex-Ante Carbon balance Tool (EX-ACT) developed by the Food and Agriculture Organization of the United Nations (FAO) (Bernoux et al., 2010; Bockel et al., 2013; Grewer et al., 2016) or other methods if more appropriate for a specific value chain (Grewer et al., 2016, 2018).

Our estimates of the GHG impact of FLW include emissions from the production of the lost or wasted food, not emissions resulting from its decomposition. This work, and most work in FLW, does not account for the possibility of increased emissions introduced by new processing methods, storage, or transportation interventions. It also assumes that production would decrease proportionate to the reduction in FLW. We calculated the impact of FLW interventions as the change in effective yields using a reference of business-as-usual (BAU) (Eq. (1)).

$$\text{FLW intervention impact} = (\text{FLW}_{\text{intervention}} \text{ x yield}_{\text{intervention}}) - (\text{FLW}_{\text{BAU}} \text{ x yield}_{\text{BAU}}) \quad (1)$$

Our analysis accounted for the three primary GHGs associated with agricultural production: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Reay et al., 2012; Smith, 2017). Management decisions, such as tillage regimes and use of cover crops, soil physical properties and environmental conditions influence if soils are a source of CO_2 to the atmosphere or a sink, taking CO_2 out of the atmosphere (sequestration). Changes in management can reduce CO_2 emissions or lead to sequestration. CH_4 is released through the normal digestive processes of livestock, particularly ruminants, as well as from manure storage, manure application to fields, crop residue burning, and flooded rice cultivation. N_2O is released when bacteria break down nitrogen fertilizers, organic matter, manure, and urine and when farmers burn crop residues. Higher emissions are associated with meat and dairy production, as compared with grains, fruits, and vegetables (Clune et al., 2017).

In Grewer et al. (2016, 2018) we present the detailed methodology for estimating GHG emissions and carbon sequestration with the Ex-Ante Carbon balance Tool (EX-ACT) as applied for these projects. In brief, EX-ACT is a bookkeeping model that accounts for multiple practices, environments, GHGs, carbon pools (5) including living and non-living material above and below ground, and carbon fluxes between pools (Schoene et al., 2007). We used EX-ACT used to estimate CO_2, CH_4, and N_2O emissions from agricultural activities and indirect CO_2 emissions from production, transport, and storage of synthetic inputs and from direct burning of fossil fuels. To account for production, transport, storage and infrastructure establishment related to fertilizer and pesticide, we used guidance from Lal (2004). We used coefficients from the International Energy Agency (USDE, 2007) to estimate electricity production emissions. We estimated emissions related to the use of fuels for farm operations using IPCC (2006). Implementing partners provided information and data on agricultural activities needed to run EX-ACT, including changes in practices with FLW interventions, FLW rates, and annual yields (Nash et al., 2017). EX-ACT estimates represent 20 years of implementation of a given intervention, which are annualized for interpretation.

Some EX-ACT submodules were developed for analysis of FtF programs (Grewer et al. 2018). We calculated GHG emissions from livestock using Tier 1 methods from IPCC (2006), including enteric fermentation, manure management, and manure deposition. Enteric fermentation methane emissions were estimated using Tier 1 methods (IPCC, 2006) except for livestock weights for cattle and sheep monitored by FtF (partial Tier 2 method, IPCC, 2006) and for camels (Dittmann et al., 2014). Changes in livestock weights due to FtF project interventions were accounted for using the Tier 2 approach (IPCC, 2006). Mitigation benefits of improved feeding and breeding projects used Tier 1 estimates (Smith et al., 2007).

Emission estimates from crop management practices followed IPCC (2006) except where noted. Burning of crop residues emits CH_4 and N_2O as a function of crop yields as reported by FtF project

(IPCC, 2006). CH_4 emissions from flooded rice were informed by FtF projects' reporting on irrigation practices and followed default values from IPCC (2006). In soils, nitrogen fertilizer is partially converted to N_2O as a function of fertilizer dose and irrigation (IPCC, 2006), inputs that were here estimated from project data on synthetic and organic nitrogen inputs and water management. We applied emissions factors for N_2O emitted from urea deep placement in rice based on direct measurements from Gahire et al. (2015).

GHG impact is the net effect of all GHG emissions and carbon sequestration due to agricultural practices or a change in practices (Grewer et al. 2018). Here, negative GHG impact indicates reductions (carbon sequestration) due to FtF activities, and positive GHG impact shows increasing emissions. All GHG impacts are converted to CO_2 equivalents (CO_2e), assuming a GWP of 34 for CH_4 and 298 for N_2O (Myhre et al., 2013).

3. Results

3.1. Commonly utilized FLW interventions

The 13 projects provided training or training plans for value chain actors to reduce FLW. The most common interventions focused on storage and processing stages, followed by activities focused on production and harvesting. Many projects mentioned potential for improvements in the transportation stage. In many cases, interventions focused on affordable technologies (e.g., hermetic storage bags) that are also simple to learn (e.g., single training session) compared to alternatives (e.g., insecticide application). Projects reported that successful technologies for reducing FLW tended to be those that functioned well, involved little capital expenditure, and reduced costs of production or marketing. Intervention strategies by stage are described in the following sections with detailed examples given in Appendix A.

3.1.1. General strategies addressing food loss and waste

Most projects used technical knowledge transfer or capacity building activities to promote FLW reduction technologies. For example, the Commodity Production and Marketing (CPM) project in Uganda trained traders and village agents on post-harvest handling of grains and seeds, such as sorting for single color beans to access good markets. During one quarter, 35 traders and 194 village agents reported 434 learning sites where they engaged with farmers to build capacity on post-harvest handling and other farm management practices. Many projects employed a "train-the-trainer" approach, in which they engaged local leaders (e.g., traders, village representatives, cooperatives) who then disseminated knowledge to their communities, often through demonstrations (e.g., farm visits) or visual guides (e.g., bean sorting posters in traders' offices).

3.1.2. Advancing production and improving harvest practices

Approximately half of the projects documented interventions to reduce food loss through improved production based on input choice(s), most often through crop varieties that have a longer shelf life and/or higher disease resistance (Appendix A). For example, the project in Honduras experimented with twelve varieties of yellow onions to test for long shelf life and diseases resistance. The project in Nigeria informed farmers on selecting disease- and pest-resistant cocoa, qualities important to buyers. Changes in input choice for livestock focused on selecting breeds with disease resistance, acquiring healthy animals, and/or animals that could be slaughtered at a younger age. In Bangladesh, trainings for livestock producers demonstrated techniques to select fit, healthy animals for slaughter. Interventions in a Rwanda project focused on financial sustainability, knowledge transfer, and decision feasibility when identifying livestock genetic qualities and breeding choices for productive and healthy animals.

Projects that aimed to reduce FLW through harvesting interventions focused on practices that optimize environmental conditions during harvesting, including those that reduce moisture that leads to mold and decay, or promote harvesting techniques that better preserve product quality (Appendix A). Specific activities aimed to reduce the spread of rot, pests or contamination during or immediately after harvest. By encouraging the use of planting and harvesting calendars to help farmers time their harvest, the project in Honduras maximized revenue and shelf life. The project in Haiti promoted the use of cutting poles when harvesting mangos to reduce sap damage to the skin of the fruit and thus increase market acceptance. In Nigeria, the frequency of cocoa bean diseases decreased due to use of wooden mallets to break open pods instead of use of machetes that transferred diseases from one pod to another.

3.1.3. Processing to increase storage and food safety

All projects aimed to decrease FLW through: a) improved product processing to increase storage time and b) hygienic measures to promote food safety. Many processing interventions also involved training; some involved new processing equipment and training to use that equipment properly. We did not consider processing interventions involving value-added products, although some projects planned activities involving preservation and longer-term storage. In Ethiopia, activities focused on evaluating and grading green coffee bean quality and documenting the traceability of products. In Haiti, interventions supported new methods of drying mangoes and other crops for export. In Uganda, farmers were able to access needed processing equipment (e.g., for threshing, cleaning, and storage). Based on recommendations by fish producers and processors, MARKETS II helped develop scalable fish processing techniques in Nigeria. In Rwanda, the project investigated and developed investment to expand processing of dairy, such as value-added milk products.

3.1.4. Physical storage and packaging

Most projects with FLW interventions included improved product storage, and included capital-intensive interventions such as providing storage containers or equipment to fabricate packaging; interventions combining education and innovation such as through training producers on new methods to store products or create storage infrastructure; and cooling or refrigeration devices and facilities for highly perishable products like meat and dairy. Farmer and processor trainings in Ghana demonstrated construction techniques to improve silos with locally accessible, often natural materials. One project in Ethiopia supported the availability of portable-bag sewing machines to increase the efficiency of storage and decrease of waste. Another project in Ethiopia provided milk containers for a more hygienic storage system. The project in Haiti leveraged storage and transportation structure improvements, including use of plastic crates, to protect fresh produce from bruising. In Liberia, the project supported trainings on the creation of refrigeration and cooling facilities and improving pest control during storage. The promotion of hermetic storage bags in Kenya decreased losses of maize stored at home.

3.1.5. Transportation

Almost half of the projects included transportation-related interventions. Many interventions in transportation also apply to storage, as it is economical and efficient for storage solutions to also be safe and efficient for transport. Some transportation interventions noted the importance of well-maintained and accessible roadways and systems to connect value chain stakeholders. A few interventions focused on strategically located collection and distribution centers in order to be accessible to a substantial number of producers, processors, and distributors. In Ethiopia, the project identified a need for improved cold-chain storage and transportation systems to improve the dairy value chain. The project in Haiti had a role in the promotion of donkey pack frames to store and protect products in vehicle-inaccessible areas and aided in the development of infrastructure, including roadway improvements, with financial support from partnerships. In Kenya, milk storage capacity increased through collection center support.

3.2. Reduced FLW

Data from activities in dairy, maize, rice, vegetables, and other products show that FLW varies greatly by product and location, as does the degree of impact from interventions (Tables 2, 3). The projects intervened to reduce FLW in multiple stages and generally achieved large reductions in FLW (Tables 3, 4). For projects with different bundles of interventions affecting GHG emissions, estimates reflect the portion of the project affected.

Table 2
Stages of intervention and impact of FLW-reducing methods by agricultural product (tonnes).

	Dairy	Maize	Vegetables	Rice	Other
Types of intervention					
Input Choice	x	x	x	x	x
Harvesting			x	x	x
Processing	x	x	x	x	x
Storage	x	x	x	x	x
Transportation	x		x		x
Impact of support					
FLW estimate BAU (t)	235,266	249,338	220,092	122,937	62,533
FLW estimate intervention (t)	155,861	110,997	112,021	38,846	29,972
Percent change	66%	45%	51%	32%	48%

Table 3
Changes in food loss and waste, effective yield, and emission intensity by agricultural product and country (project) before and after project interventions.

		Food Loss and Waste (%)		Effective Yield (t/ha or 1000 L/head)		Emission Intensity (tCO_2e/t product or tCO_2e/1000 L milk)	
	Product	BAU	Intervention	BAU	Intervention	BAU	Intervention
Dairy							
Ethiopia (CMVCD)	Camels	50%	10%	0.28	0.70	1.77	1.95
Bangladesh (LPIN)	Cattle	17%	7%	0.53	1.00	1.50	1.64
Kenya (KAVES)	Cattle	5%	4%	1.44	2.81	3.40	2.44
Rwanda (Rdairy)	Cattle	30%	5%	0.56	1.20	2.14	2.41
Maize							
Cambodia (HARVEST)	Maize	30%	10%	3.66	7.74	1.48	1.93
Ethiopia (AGP-AMDe)	Maize	23%	12%	2.70	3.86	0.64	0.96
Ghana (ADVANCE II)	Maize	30%	10%	0.97	3.10	0.22	−0.04
Haiti (Chanje)	Maize	30%	16%	0.56	3.44	0.00	−0.24
Honduras (ACCESO)	Maize	20%	10%	0.94	3.78	0.47	0.01
Kenya (KAVES)	Maize	15%	9%	1.56	2.82	0.35	0.72
Nigeria (MARKETS II)	Maize	13%	10%	1.53	4.64	0.32	0.12
Uganda (CPM)	Maize	25%	17%	1.28	2.66	−0.11	−0.31
Zambia (BLA)	Maize	5%	3%	1.58	1.82	1.10	−1.49
Vegetables							
Cambodia (HARVEST)	Vegetables	30%	10%	3.26	16.52	1.48	1.93
Haiti (Chanje)	Plantain	32%	15%	8.84	17.26	0.00	2.17
Honduras (ACCESO)	Plantain	20%	5%	12.97	46.21	0.42	2.32
Kenya (KAVES)	Potato	18%	8%	5.74	14.72	1.32	−0.75
Nigeria (MARKETS II)	Cassava	38%	20%	7.50	18.83	0.00	0.40
Rice							
Cambodia (HARVEST)	Rice	20%	5%	1.60	3.04	5.14	2.93
Ghana (ADVANCE II)	Rice	20%	10%	1.81	3.53	1.96	1.39
Haiti (Chanje)	Rice	27%	15%	1.61	4.47	6.60	3.62
Liberia (FED)	Rice	30%	22%	0.70	2.35	0.00	0.74
Nigeria (MARKETS II)	Rice	13%	10%	1.84	5.16	2.30	0.40
Zambia (BLA)	Rice	15%	3%	1.11	2.91	1.33	1.22
Market goods							
Ethiopia (AGP-AMDe)	Coffee	18%	11%	0.61	0.94	−0.70	−0.87
	Wheat	13%	7%	2.18	3.16	0.42	0.39
	Sesame	10%	5%	0.28	0.48	0.00	0.32
Nigeria (MARKETS II)	Soybean	20%	5%	0.48	2.28	0.00	−0.72
Haiti (Chanje)	Beans	30%	15%	0.42	1.02	0.00	−0.83
Haiti (Chanje)	Mango	25%	16%	5.63	6.28	0.00	−8.07
Uganda (CPM)	Coffee	7%	4%	1.61	3.32	0.25	0.28
	Beans	18%	11%				
Zambia (BLA)	Groundnut	1%	0%	0.84	1.02	0.00	−0.29
Zambia (BLA)	Soybean	30%	10%	0.77	1.53	0.00	−1.45

Table 4
Interventions in FLW in specific FtF projects and food products spanned many stages of the value chain. Post-harvest is noted as PH,; Household is noted as HH.

	Input Choice(s)	Harvesting	Processing	Storage	Transportation
Honduras	(ACCESO)	**Vegetables (onion):** Varieties	**Coffee:** Harvest techniques	**Coffee, maize:** Processing **Fruit (Passionfruit):** Processing, freezing **Vegetables (Sweet potatoes):** cleaning, sorting, grading **(Potato):** Taught best practices (PH handling, processing)	**Fruit (Passionfruit):** Packaging **Maize:** Storage (metal silos) **Vegetables (Potato):** Packaging to meet quality standards. **(Sweet potato):** packaging for export.
Maize:	Developed transportation logistics				
Ghana	(ADVANCE II)		**Maize, Rice:** Harvesting (optimal time), monitor moisture	**Maize, Rice:** Equipment/ technologies	**Maize, Rice:** Storage
Ethiopia (AGP-AMDe)	**Chickpea:** Varieties	**Chickpea, Wheat:** Harvesting, threshing technologies.	**Coffee:** Processing **Grain:** Grading tools, market-linked technical support. **Maize:** PH handling equipment	**Maize:** Mobile bag stitching machines; fumigation sheets **Wheat**: Warehousing	
Zambia (BLA)		**Rice, maize, soybeans, groundnuts:** PH handling	**Rice, maize, soybeans, groundnuts:** PH processing	**Rice, maize, soybeans, groundnuts**: Packaging; Depots for crop storage.	
Ethiopia (Camel Milk)		**Dairy:** Hygiene, handling	**Milk:** cooling facilities	**Milk:** Storage containers, cooling facilities	**Milk:** Improved transportation
Haiti (Chanje Lavi Plante)		**Corn, beans, rice:** Harvest practices **Mango, plantain:** Post-harvest handling	**Mango:** Processing to shelf-stable dried product.	**Corn, beans and rice:** Portable storage silos; Storage conditions (humidity control) **Mango:** Storage in plastic crates	**Corn, beans, rice:** Jute bags **Mango:** Donkey pack frames for transport to vehicles; Rehabilitated key feeder roads
Uganda (CPM)		**Maize:** PH handling **Coffee:** PH handling, hygiene **Beans:** Equipment meeting womens' needs; PH post-harvest practices	**Beans:** PH processing, grading; Aggregation **Coffee:** PH processing **Maize:** Drying, moisture meters (less spoilage); Integrated drying, cleaning, grading, bagging grain handling system; Youth provide handling equipment	**Maize, beans and coffee:** Proper storage **Maize:** Storage construction; Sanitary conditions; Bagging, packing, storage bags.	**Maize:** Adaptation of system improvements to address quality deterioration in transportation.
Liberia (FED)	**Rice:** New rice seed production	**Rice:** Technology transfer (manual threshers)	**Rice:** PH processing and local capacity for technology fabrication/construction. Financing for commercial processers; Warehouse (processing equipment) **Vegetables (Cassava):** Small-scale processing (reduce bulk); processing centers	**Cassava, rice:** HH storage technologies (reduce loss, improve food safety); Centralized storage **Rice:** Rat guard fabrication, installations; Store surplus **Vegetables:** Cooling facilities; Packaging	**Vegetables:** Use of plastic crates
Cambodia	(HARVEST)			**Fish:** Women producers (fish paste) in PH processing **Rice:** Increased mills' capacity to purchase from small holder farmers; PH processing equipment	**Fish, rice:** Storage
Kenya (KAVES)	**Dairy:** Farm inputs (animal feeds, fodder, animal health, artificial insemination services).	**Maize:** Harvest at optimal moisture (food safety) **Dairy:** Efficient collection systems; PH handling systems (reduce physical waste, quality erosion).	**Dairy:** Added value, shelf life products; Cooler establishment **Maize:** PH processing (mobile equipment); management of aflatoxins, impurities **Fruit (Passion fruit, mango):** Juice processing	**Potato:** Storage with diffused light systems **Maize:** Silage bags, cost-effective storage systems	
Bangladesh (LPIN)	**Meat:** Increased quantity of each meat product; Selection of healthy animals for slaughter	**Meat:** Safety, quality; hygienic techniques; Slaughter infrastructures; Facilitate financing to	**Meat:** HH preservation, handling and use **Dairy:** HH preservation, use; Processing facilities, pasteurization plant; Develop/	**Dairy:** HH production of value-added and prolonged shelf-life products	

Table 4 (*continued*)

	Input Choice(s)	Harvesting	Processing	Storage	Transportation
		upgrade slaughtering facilities	disseminate recipes		
Nigeria	(MARKETS II)	**Cocoa:** Varieties (yields, disease/ pest resistance, desired end user characteristics); cocoa specific fertilizer. **Rice:** Varieties (yield, desired end user characteristics)	**Vegetables (Cassava):** Harvesting, PH handling **Grains, soybean:** Harvest techniques **Fish:** Harvesting practices (minimize fish losses); Handling **Rice:** Technologies reduced contamination/ rejection, losses	**Vegetables (Cassava):** Processing technologies (drying, grading) **Cocoa:** Processing (drying, fermentation, extraction) **Fish:** Processing to maintain quality and shelf life; Equipment development; Taught youth techniques. **Rice:** Technologies for women specific tasks **Rice, soybean:** Promoted job creation in processing	**Vegetables (Cassava):** Storage practices to minimize loss **Soybean:** New bagging activities **Rice:** Bagging (minimize losses, paddy wastage, maintain high quality); Moisture meters in storage **Grains:** Farmer training
Cocoa, fish:	Transportation practices **Rice:** Warehouse centrally-located to farmers.				
Rwanda (RDCP)	**Dairy:** Nutrition, forage production/ feed, breeding/genetics, disease resistant livestock, animal health	**Dairy:** Milking procedures and handling; Hygienic harvesting practices; Good basic hygiene	**Dairy:** Refrigerated distribution centers; Value-added products; Quality testing; Equipment cleanliness enforcement; Safe disposal of waste; Screening, segregating (quality, traceability).	**Dairy:** Temperature controlled, sanitary storage	**Dairy:** Refrigerated storage; rapid product transportation

3.2.1. Dairy

Under business-as-usual approaches, FLW ranged from 5 to 50% for dairy. Bundles of FLW interventions focused on improved inputs (e.g., feed, animal health, animal breeding), hygiene and handling (e.g., harvesting in the shade), ensuring quality through sanitary storage and proper temperatures in cooling facilities from processing through transport, testing of milk quality, sorting and segregating by quality, increasing household use of dairy, or creating value-added or longer shelf life products (e.g., yogurt, ghee) (Table 4, Appendix A). The four projects in this study reduced FLW (Table 3) by an average of 11% (geometric mean, std. dev. 15%), with the greatest reductions realized in camel (Ethiopia, 40% reduction) and cow (Rwanda, 25% reduction) herds. Activities in Kenya and Bangladesh estimated moderate reductions in FLW (10 and 1.5 percentage point reductions, respectively). Projects in Ethiopia and Rwanda reported greater business-as-usual levels of FLW than the projects in Bangladesh and Kenya.

3.2.2. Maize

Projects were able to reduce business-as-usual FLW in maize from 5 to 30% to 3–17% with interventions. Most bundles of FLW interventions in maize focused on harvesting (e.g., optimal moisture, improved handling practices to avoid contamination), processing (e.g., improved technologies, equipment or systems, drying and use of moisture meters particularly to avoid aflatoxins, exclusions of impurities introduced with BAU processing), storage (e.g., metal or elevated silos, bagging equipment or use of hermetic bags, sanitary storage conditions) and transportation (e.g., improved logistics to reduce loss or deterioration or quality) (Table 4, Appendix A). The nine projects studied reduced FLW in maize, a staple grain crop in many countries, by an average of 8% (geometric mean, std. dev. 6%). The project in Ghana reported a 20% reduction in FLW, the largest change in maize in our analysis, due in part to improved storage from construction of new silos.

3.2.3. Vegetables

Projects estimated business-as-usual FLW for vegetables of 18–38%, though estimates varied widely, based on crop and level of market development. Only one project specifically addressed input selection (Honduras), testing varieties of onion for yields and storage potential. Processing (cleaning, sorting, grading) and storage (packaging, cooling) were bundled in two projects (Liberia, Honduras). Use of crates for transport were used in one project (Liberia) (See Table 4, Appendix A). Reductions of 5–20% were reported through project interventions. The project in Cambodia estimated a 20% reduction in FLW due to improvements in post-harvest handling. Projects in Haiti and Honduras aimed to reduce FLW of vegetables through improved storage and transportation. We found the projects achieved a consistent range of FLW reductions (17% based on geometric mean, std. dev. 3%) in a range of vegetables, from starchy roots like cassava and potato to plantains and cucumbers.

3.2.4. Rice

Projects estimated that business-as-usual FLW of 13–30% in rice was reduced to 3–22% due to project interventions. FLW intervention bundles for rice spanned 3 or more stages of the value chain. Input choices included new rice seed production or varieties selected for yield and desired end user characteristics. Harvest interventions included optimal timing, monitoring moisture, technology transfer (e.g., new or improved threshing equipment, practices to reduce moisture or soil contamination to harvested product). Processing interventions reduced losses, such as by introducing new technologies, including local fabrication of machinery or facilities. Storage improvements focused on physical storage space (e.g., depots, warehouses), humidity control, exclusion of pests, and storage appropriate for households (e.g., portable silos). One project (Haiti) introduced the use of jute bags to reduce product deterioration in transportation. FLW reductions in rice were modest (8% geometric mean) but consistent (3% std. dev.). For example, Cambodia's rice sector suffers from FLW of 20–30% from harvest through transport until processing. Project activities in Cambodia achieved a 20% reduction in FLW due to interventions in storage and processing (drying). In Nigeria, the project saw little change (2.5%) in FLW, as it focused on milling of rice and other crops.

3.2.5. Market goods

The 13 projects also focused on FLW in a variety of locally important foods, including fish, fruits, perennials, legumes, and grains. For fish, interventions bundled two to three stages of the value chain, including harvesting and handling practices, processing (e.g., fish paste and products with shelf life, equipment development, youth training), storage, and transportation practices (Cambodia, Nigeria) (Table 4). Passionfruit and mango interventions (Kenya, Honduras) focused on processing of raw fruit to pulp or juice and storage with improved packing or freezing, often for export (e.g., tropical fruit juices). In Nigeria, cocoa interventions were applied in input choice of varieties (improved yields, disease and pest resistance, desired end user characteristics) cocoa-specific fertilizer, processing improvements (drying, fermentation and extraction), as well as improved transportation practices. Coffee interventions spanned harvest (improved harvest techniques, handling and hygiene) and processing (reduced time from harvest to drying, solar drying, improved tracing, testing and grading, use of tarps and drying trays to reduce mold) (Table 4). The Uganda project also focused on improving storage conditions for coffee (Appendix A). Grain interventions (Table 4) targeted harvest techniques, processing, and storage through training of farmers on improved practices, as well as promoting job creation in soybean processing (Nigeria). Estimated business-as-usual FLW in these value chains ranged from 1 to 30% and were reduced to 0–16% through project interventions. Mixed market and subsistence crops (e.g., beans, coffee, nuts) experienced modest changes (7% reduction in FLW based on geometric mean, std. dev. 6%), but the changes were important to farmers as they were in high value crops.

3.3. Impact of FLW reductions on GHG emissions

FLW interventions in the 13 USAID FtF projects examined could provide GHG emission savings of 384,000 tCO_2e/year (Fig. 4). This is equivalent to emissions from almost 900,000 barrels of oil consumed, according to the EPA's GHG equivalency calculator (EPA, 2017).

Estimated GHG emission reductions from FLW interventions in dairy make up almost 90% of total emission reductions. Amongst the four projects intervening in the dairy value chain, activities in Ethiopia and Rwanda contribute the most to GHG reductions

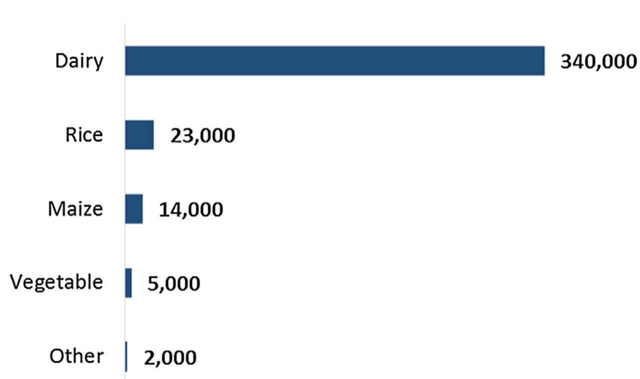

Fig. 4. Estimated emission reductions from FLW by agricultural product.Data in tCO_2e is rounded to the nearest thousand.

(192,542 and 119,365 t CO_2e, respectively); both projects estimated about 80% reductions in FLW. In contrast, the activities in Kenya and Bangladesh estimated 2–10% decreases and therefore lesser emission reductions (15,904 and 11,770 t CO_2e, respectively). Appendix A provides examples of interventions implemented by projects.

3.3.1. Dairy

Projects had an average 4% decline in GHG emissions (2.20±0.73 to 2.11±0.33 tCO_2-e $head^{-1}\,year^{-1}$) with interventions, although this trend driven by the largest dairy project (KAVES/Kenya) with 435,000 head (cattle) with a 28% emissions reduction (Table 3). Projects in Ethiopia (247,445 head of camels), Bangladesh (71,150 head of cattle), and Rwanda increased emissions roughly 9–12%.

3.3.2. Maize

Interventions in FLW largely led to reductions in emissions for maize (63% reduction on average), but with a wide range (reduced emissions by 231% to increased emissions by 106%) (Table 3). Averaged across all projects, emissions were reduced from 0.5 to 0.19 tCO_2-e $ha^{-1}\,year^{-1}$ or 63% (0.31 tCO_2-e $ha^{-1}\,year^{-1}$ from BAU emissions) but not all projects reduced emissions. Six out of nine projects reduced emissions for maize. HARVEST was the smallest project by area (<1000 ha) but had the largest BAU emissions (1.48 tCO_2-e ha^{-1} $year^{-1}$) that increased with interventions (1.93 tCO_2-e ha^{-1} $year^{-1}$) largely due to crop management unassociated with FLW interventions that increased yields from 3.36 to 7.74 t/ha $year^{-1}$ after accounting for FLW.

3.3.3. Vegetables

Interventions in vegetable products averaged 88% increase in GHG emissions intensity (0.64 to 01.21 tCO_2-e ha^{-1} $year^{-1}$) but with wide variation (Table 3). For potatoes in the Kenya project, emissions were reduced 156% (1.32 to −0.75 tCO_2-e ha^{-1} $year^{-1}$). In Honduras, plantain production increased emissions 4.5× nearly in proportion to increases in yields.

3.3.4. Rice

Interventions in rice production decreased emissions by 40%, on average (2.89 to 1.72 tCO_2-e ha^{-1} $year^{-1}$). The largest project by cultivated area (114,000 ha), Nigeria (MARKETS) had an estimated emissions that rose modestly to 0.40 tCO_2-e ha^{-1} $year^{-1}$ while yields, after accounting for FLW, nearly tripled. Projects on the scale of 2000 to 12,000 ha decreased emissions intensity by 8 to 45% (Table 3).

3.3.5. Market goods

This category of agricultural products had very low annual emissions by area prior to interventions (average – 0.05 +/– 0.26 tCO_2-e ha^{-1} $year^{-1}$), with many production practices having no estimated emissions (Table 3). With interventions, emissions intensity decreased an average of −0.41+/– 2.0 tCO_2-e ha^{-1} $year^{-1}$ with the variation largely from a mango project in Haiti (Chanje) (−8.07 tCO_2-e ha^{-1} $year^{-1}$ after interventions). Emissions in coffee show how different production systems, geographies and other factors can lead to very different outcomes (e.g., negative emissions in one project and positive emissions in another).

4. Discussion

Agricultural development and food security projects typically adopt FLW activities as part of a strategy to increase productivity, household income, and food availability. Results of this analysis suggest that reducing FLW is also an under-recognized opportunity for mitigating greenhouse gas emissions.

Our examination of a range of FLW interventions by stage (input, harvest, processing, storage, and transportation), product (dairy, maize, rice, etc.) and country (12 countries on 3 continents) provides new insights on specific ways that FLW interventions can contribute simultaneously to food security and emission reductions. These results should bolster FLW efforts in future food security, agriculture, and climate change mitigation projects.

Based on our analysis, USAID's current market-systems approach to FLW contributes to emission reductions. Interviews and project documents point to the need for multiple or diverse strategies that address FLW challenges specific to particular crops, value chains, and country contexts. This synergistic approach supports previous research findings that context-dependent strategies are necessary (Sheahan and Barrett, 2016).

Emission reductions from FLW interventions in dairy account for almost 90% of the total FLW emission savings reported in this analysis. This scale of change is possible because dairy is emission-intensive and because these dairy systems have high rates of FLW, reflecting the high perishability of dairy.

Some FLW interventions result in small reductions per area or per animal unit, yet net benefits are significant at the project, regional, or national scales because of the sheer size of the value chain. For example, seemingly moderate impacts of interventions in Kenya reduced dairy FLW from 5% to 3.5%, a reduction of 30% that had a large impact in available product (1400 L/head increased to 2800 L/head) and emission intensity (2.4 reduced to 1.2 tCO_2-e/1000 L milk), but the net impacts on emissions were large when considering the 435,000 animals involved. Reductions in emissions during maize production with interventions in Ghana (ADVANCE II) were modest (0.22 to −0.08 tCO_2-e ha^{-1} $year^{-1}$) but were carried out over 28,200 ha for a total GHG savings of 169,000 tCO_2-e if carried out over 20 years. Conversely, in Cambodian croplands, there was a seemingly high rate of FLW reduction (67% per tonne of vegetables), but a small implementation area (131 to 2095 ha) that resulted in a relatively low reduction in net FLW and emissions.

This analysis provides data that can guide future FLW interventions – especially those with an interest in achieving climate change mitigation co-benefits. Likewise, the methods used in this study should inform projects of the need to monitor and evaluate FLW. Planned and systematic collection of data on agricultural yields and losses, such as carried out by these projects, will improve FLW estimates, contribute to more effective project implementation, and serve productivity, food security, household income, and climate change mitigation goals. Our experience shows that projects lack a common framework for reporting FLW interventions, making it difficult to execute cross-project comparisons, learning, and validation of estimates. There is also a need to verify FLW and FLW-reduction estimates via independent methods. Scientifically rigorous and comparable monitoring and evaluation systems would allow for systematic analysis of the technical efficacy, cost-effectiveness, and potential adoption hurdles of FLW interventions across local contexts and production systems.

This analysis demonstrates the potential of FLW interventions to reduce emission intensity. It is important to note that emission intensity is different from net emissions reduction. If future agricultural production increases or does not decrease, the potential for net emissions reductions may be small. Conceptually, increases in effective yields or available food due to reduced FLW may contribute to less demand for production, and reduce resources needed for production, such as energy or fertilizer (Kendall and Pimentel, 1994) that contribute to GHG emissions. However, developing or growing markets may not see a drop in production with FLW interventions (e.g., Gromko, 2018), and it is likely that if low demand elasticity (typical of food) causes a drop in production for some products, it would not be proportional to the gains in effective production realized by reduced FLW. As Gromko and Abdurasalova (2019) point out, decreases in emission intensity are all the more important given increasing demand for food products. Economic models of FLW suggest FLW reductions may incentivize increased production due to increased efficiency, which could actually increase absolute emissions. It is possible that production would increase even more in the business-as-usual case with increasing demand and constant rates of FLW, meaning that reducing FLW would reduce emissions versus the business-as-usual case, but this depends on efficiency of production and costs (de Gorter, 2014).

We show that market-based approaches can achieve FLW and emission intensity reductions. This work, and most work in FLW, does not account for the possibility of increased emissions introduced by new processing methods, storage, or transportation interventions that could be estimated with full life-cycle analysis. Using a broader framework for FLW analyses could expand the range of project interventions while accounting for potential additions in emissions. However, we expect that emissions from FLW interventions will remain lower than the business-as-usual development trajectory, even in a life-cycle analysis perspective. Achieving FLW and emissions reductions as a development strategy calls for more rigorous monitoring and evaluation of FLW emission impacts and context-specific interventions that can be scaled up in a gender- and socially inclusive manner.

5. Conclusion

FLW interventions analyzed in this study were designed to increase food security, yet we find that reducing FLW can contribute to climate change mitigation as well. These projects are examples of how agricultural development can increase food security by increasing productivity while decreasing emission intensity. This analysis also shows that market-based approaches can achieve FLW and emission reductions. Few FLW research studies have investigated interventions across a range of value chains or in multiple countries, likely due to the difficulties in collecting and synthesizing multi-country estimates. Published studies also have not estimated adequately the emissions impact of FLW initiatives in developing countries, which was possible here by investigating FLW in FtF projects across extended value chains and wide country contexts.

Because reducing FLW leaves more food available for consumption and sale while reducing emission intensity, it contributes to the overarching goal of "bending the curve" – decoupling trajectories of economic growth and GHG emissions. The FtF projects also illustrate how climate-smart agricultural development can enhance food security – the primary objective for these projects – by increasing effective yields through reducing FLW while also decreasing emission intensity.

Given increasing demand for food from a growing population in a changing climate, unnecessary food loss and waste is no longer affordable for people or the climate. This study should serve as an impetus for development organizations to embrace FLW reduction as a livelihood, food security, and climate change mitigation strategy.

CRediT authorship contribution statement

Gillian L. Galford: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Olivia Peña:** Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Amanda K. Sullivan:** Data curation, Formal analysis, Investigation, Writing - review & editing. **Julie Nash:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing - original draft. **Noel Gurwick:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing. **Gillian Pirolli:** Data curation, Formal analysis, Investigation, Methodology, Writing - original draft. **Meryl Richards:** Conceptualization, Writing - review & editing. **Julianna White:** Project administration, Writing - review & editing. **E. Lini Wollenberg:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134318.

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