Exploring the complex relationships between food loss and waste, climate change and the environment to support informed sustainable food system transformation decisions with a focus on sub-Saharan Africa

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Abstract

Food loss and waste (FLW) reduction is key to transforming food systems to deliver food security, while responding to climate change and reducing other environmental impacts. Food production and postharvest systems differ with location, reflecting the diversity of agro-ecological and socio-economic environments and the drivers influencing them. The interaction between drivers and environments, practices and products influence food systems and their related greenhouse gas emissions and other environmental impacts. These factors also influence the level of food loss during or after harvest or food waste at retail or consumer level. This think-piece examines the inter-relationships between climatic change, environment, and FLW within a broader food systems framework. We use the case study of maize in Malawi to explore these relationships. This analysis unpacks the issues and suggests an approach for supporting decision-makers in making a more informed assessment of how to achieve FLW reduction, taking the complexity of food systems, their multiple drivers of change, diverse stakeholder interests/ influence and the need to operate with very incomplete knowledge into account.

Keywords: food loss and waste, postharvest loss, environmental impact, trade-offs, carbon footprint, sub-Saharan Africa

1. Introduction

Our food systems are a major cause of climate change, land use change, natural resource depletion and degradation, pollution and biodiversity loss. Human population and income growth projections suggest that the environmental effects of our food system could be 50–90% greater in 2050 compared to 2010, taking us beyond the planetary boundaries that have been defined as a safe operating space for humanity (Springmann et al., 2018, HLPE, 2020).

Despite these environmental impacts, estimates suggest that more than one third of the food produced on our planet is lost or wasted in the food system (WWF-UK, 2021; UNEP, 2021). Food loss and waste (FLW) reduction is now identified in global analyses as a key opportunity to help transform food systems to deliver food security, while responding to climate change, reducing environmental impacts and contributing to several other Sustainable Development Goals (SDGs) (Springmann et al., 2018, Smith et al., 2020, HLPE, 2020; Project Drawdown, undated). In 2015, world leaders “committed“ to reducing FLW globally by 2030 (SDG 12.3) and in 2014, Sub-Saharan African (SSA) leaders committed to halving postharvest losses (PHLs) by 2025 (African Union Malabo Declaration 3.3b).

This article explores aspects of the complex relationships between climatic change, environment, and FLW within a broader food systems framework, and with a particular focus on Malawi and SSA where climate change, environmental change and food security and nutrition are major issues. This exploration aims to contribute to an approach for supporting decision-makers in making an informed assessment of what is needed to achieve FLW reduction, taking the complexity of food systems, their multiple drivers of change, diverse stakeholder interests/ influence and the significant existing knowledge gaps into account.

2. Conceptualising Food Systems

Food production and postharvest systems differ over space and time, reflecting diverse agro-ecological and socio-economic environments and the drivers influencing them. Interactions between the drivers and environments, practices and products influence food-related greenhouse gas (GHG) emissions and other environmental impacts. These factors also determine FLW.

Several frameworks have been developed to help visualize and analyze these complex, diverse, interconnected and often nested food systems, each of which emphasises different dimensions. The High-Level Panel of Experts (HLPE) 2020 report on Food Security and Nutrition (Figure 1) emphasizes food and nutrition outcomes. The Economics of Ecosystems and Biodiversity (TEEB) AgriFood framework highlights the role of the existing natural, produced, human and social capital base in shaping the flows, outcomes and impacts of food systems(see supplementary information Figure S1). Both frameworks identify separate activity stages within the food supply chain or agri-value chain. FLW can occur for different reasons during these different activities, and will differ by place, product, practice, environmental conditions, timing, and intended use (Stathers et al., 2013). A recent think-piece by the World Bank illustrated the reducing quantities of food remaining along the supply chain, while identifying key policy objectives and possible policy inputs for reducing FLW (World Bank, 2020).

3. Food Loss and Waste, Climate Change and the Environment in a Food Systems context: focus on Malawi and Sub-Saharan Africa more broadly

Drawing on the HLPE and TEEB conceptual frameworks, we explore the different capital stocks or assets, trends and drivers of change in food systems and how they impact on, and are themselves impacted on, by FLW. To ground this exploration, we focus on Malawi specifically and extrapolate to

SSA more broadly. To contextualise the linkages between FLW, climate change and the environment in Malawi, we begin by examining the key assets, trends and drivers influencing their food systems using the following clusters: biophysical and environmental; demographic; technology, innovation and infrastructure; economic and market; political and institutional; and socio-cultural.

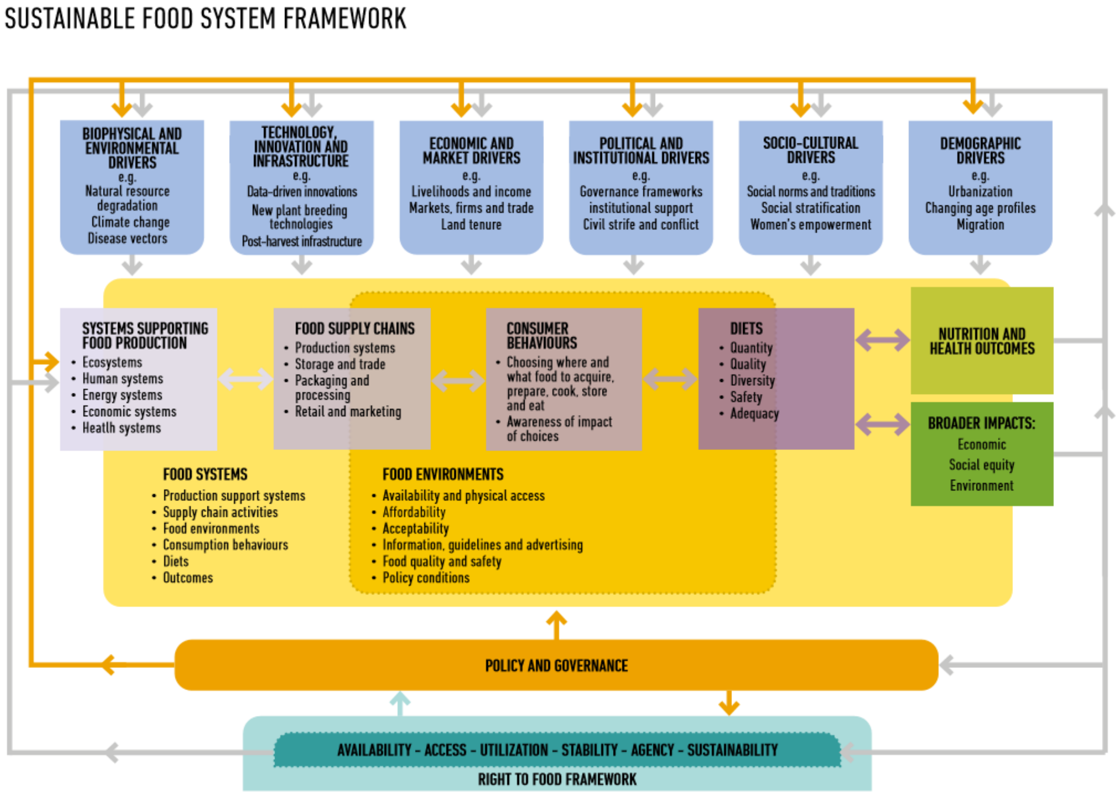


Figure 1 The Sustainable Food System Framework (Source: HLPE, 2020)

3.1 Biophysical and environmental food system assets, trends and drivers

Forest loss and degradation: Between 1972-1992, over half of Malawi's original forests were lost (World Bank, 2019). While new forests have been established through afforestation, regeneration and reforestation (resulting in net loss of 5% (1972 to 2009) (Bone et al., 2017)), there are inevitably major differences in terms of biodiversity. From 1991 to 2010, Malawi's natural forest cover declined by 9%, while the land area allocated to agriculture grew by 9% (Vargas & Omuto, 2016). Much of the forest loss has been driven by agricultural expansion.

Degradation of forests has also occurred due to overharvesting of firewood and charcoal (supplementary Figure S2), which accounts for a much larger share of forest-sourced emissions than forest clearance and conversion (World Bank, 2019).

Land use and degradation: Agriculture accounts for 60% of Malawi's total land area (FAOSTAT, 2022) (Figure 2) and most suitable land is already being cultivated (Li et al., 2021). Smallholders produce 90%+ of the maize produced (Lindsjö et al., 2021); and this crop occupies 80% of smallholder-cultivated land (IFAD, 2011 in Aberman et al., 2015). Land degradation is widespread, with up to 60% of land affected by soil erosion and nutrient loss (Mungai et al., 2016; Snapp, 1998, World Bank, 2019, Li et al., 2021).

Outcomes of these land and forest trends: Soil loss contributes to agricultural yield losses of 4-25% and food shortages (World Bank, 2019). Forest loss translates into losses of habitats, biodiversity, medicinal plants, timber and non-timber products, and food. This is particularly detrimental for poorer households who depend on them for dietary diversity (Vargas and Omuto, 2016; Mulungu and Manning, 2019; Hall et al., 2019).

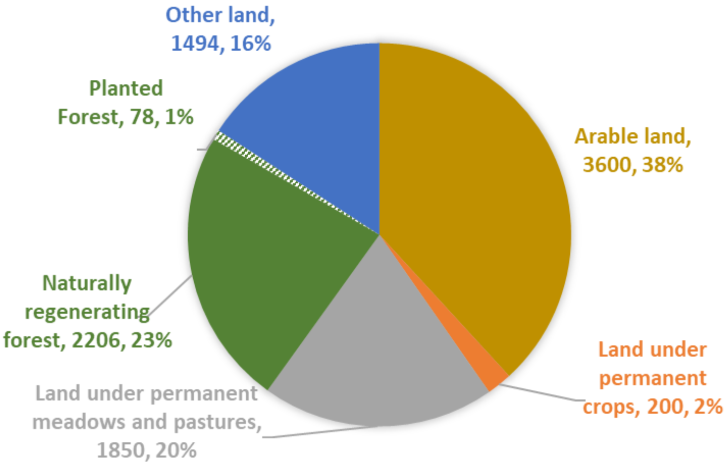


Figure 2 Land use in Malawi in 2019 (1,000ha) [Country total area = 11,848,000 ha (including 2,420,000ha inland waters)] (Source: FAOSTAT, 2022)

Biomass energy: Firewood, charcoal, and crop residues are the main sources of energy for 98% of the population, being used primarily for cooking along with activities such as tobacco curing and brick burning. Households use 92% of Malawi's biomass energy (GOM, 2009).

Declining terrestrial and aquatic biodiversity. Although protected areas account for over 10% of Malawi's area, and despite biodiversity's significant contribution to the economy and livelihoods, biodiversity is generally declining (GoM, 2015a). Ensuring sustainable use of natural resources while addressing poverty and identifying alternative livelihoods is a major challenge, alongside weak institutions, programme implementation and lack of a legislative framework around biodiversity (GoM, 2015a).

Water availability: Malawi has the lowest water availability per capita of its neighbouring countries and this is rapidly decreasing (World Bank, 2019). With less than 1,400m3/year of available total renewable water resources per person, Malawi is one of the world's most water stressed countries (Fraser et al., 2018).

GHG emissions: By global standards Malawi's GHG emissions are very low at ~0.1 tons carbon dioxide equivalent (CO2e) per capita (World Bank, 2019). The main sectors contributing to GHG emissions are agriculture (16%), forestry and other land use (AFOLU) (78%) and energy (4%). Between 2015 and 2040, Malawi's total annual GHG emissions are expected to rise by around 38% with the proportion of emissions from energy expected to increase, and from forestry to decrease (GOM, 2015b; World Bank, 2019) (Figure 3).

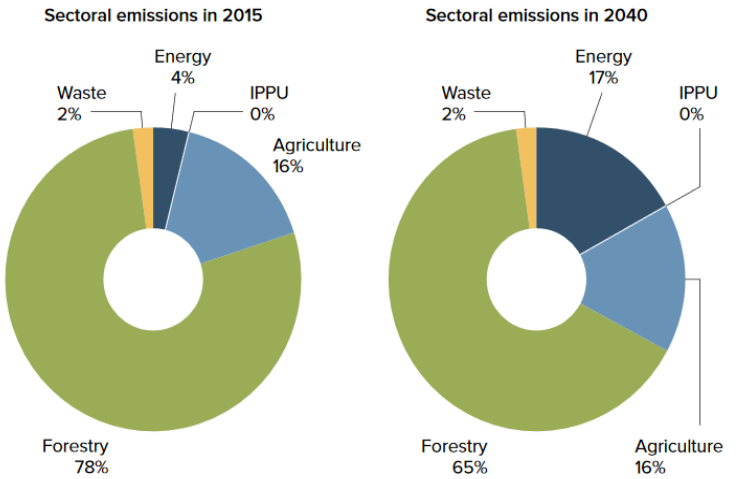


Figure 3 Malawi's GHG emission profile 2015 and projected profile for 2040 (Source: GoM, 2015b in World Bank, 2019)

Climate change: Malawi's climate is relatively dry and strongly seasonal, with 95% of annual rainfall occurring during the warm-wet season (November to April). Mean annual temperature increased by 0.9°C from 1960 to 2006; alongside an increase in hot days and hot nights. Year-to-year variability in rainfall is too high to identify long term trends (McSweeney et al., 2010). Malawi is highly vulnerable to shocks such as, droughts, floods and extreme storms. These shocks have a major influence on the economy and levels of poverty (two thirds of households have moved in and out of poverty in the period since 1998) (PVA, 2007).

Future climatic projections include an increase in mean annual temperatures by 1.1 to 3.0°C by the 2060's, and by 1.5 to 5.0°C by the 2090's. Monthly rainfall changes are uncertain, however, all models consistently project increases in the proportion of rainfall falling in heavy events. Climate change made extreme rainfall heavier and more likely to happen during several back-to-back storms and cyclones in early 2022 (Otto et al., 2022). The number of days of consecutive dry spell is very critical given the agricultural dependence of the nation.

Malawi's agri-food system is characterized by a high degree of uncertainty and volatility. It is highly reliant on rainfed smallholder agricultural production, particularly of maize. It is therefore highly vulnerable to weather and other ecological pressures e.g., fall armyworm (White, 2019). Interactions between ecosystems, transboundary impacts and the socio-economics of the agricultural sector threaten the wider stability of the food system (Warnatzsch and Reay, 2020).

Projections regarding the impact of climate change and variability (CC&V) vary widely, from a decrease in maize yield of up to 14% to an increase of up to 25% by 2050, depending on assumptions made in terms of future climate and in crop modelling (Warnatzsch and Reay, 2020). As well as production, the postharvest systems and levels of FLW will be affected by CC&V and the responses to it (Stathers et al., 2013).

The environmental challenges are complex and interrelated, with underlying and proximate drivers influencing the natural capital base.

3.2 Demographic food system assets, trends and drivers

Between 2008-2018, Malawi's population increased by 35% to 17,563,749 and is expected to double by 2042. The population is very young, with two thirds of people under 24 years and a median age of 17 years (NSO, 2008; NSO, 2019).

Population density is 186 people/sq km. The average area of land per household was 1.4 acres in 2016/17 (NSO, 2017). An increasing share of rural households are becoming deficit producers of staple food. Only 16% of the population live in urban areas; a marginal increase from 14.4 percent in 1998 (NSO, 2019). Inadequate consumption of food was reported by 64% of the population in 2016/17 (69% in rural areas) (NSO, 2017).

Malawi is listed as a Low-Income Food-Deficit Country (LIFDC) by the United Nations, with high levels of poverty, malnutrition, and undernutrition. Wealth per capita (in terms of capital assets) is low compared to other low-income countries and SSA. Malawi is still highly dependent on its natural capital, which remained constant at 43% from 1995 to 2014, while human capital increased only slightly and produced capital shrank (World Bank, 2019)

3.3 Technology, innovation and infrastructure food system assets, trends and drivers

Agricultural technology and innovation processes have focused heavily on increasing crop productivity, particularly the development and promotion of maize hybrids in conjunction with inorganic fertilizer.

There has been relatively little investment in postharvest agricultural interventions such as trials on new storage technologies (protectants, hermetic bags etc.), cassava processing. Systematic reviews on PHL reduction interventions across SSA highlight how attention has been focused on cereals, particularly maize, and on the household-level storage stage (Stathers et al., 2020; Affognon et al., 2015).

Poor infrastructure, uneven and deteriorating power access, exacerbate volatility and vulnerability of the (maize-based) food system (White, 2019). Energy use within Malawi's food system is highly dependent on natural capital. Transport costs are high, with explanations including powerful trucking lobbies and minimal competition (Roberts and Vilakazi (2016) in White, 2019).

Smallholders are perceived to lack on-farm storage infrastructure, but postharvest knowledge and skills alongside appropriate storage infrastructure are key. Farmers who lack good storage facilities or skills, or need to repay debts, commonly sell much of what they produce soon after harvest and then later need to buy food. As farmers increasingly enter markets to purchase food, national food supplies decrease and prices increase (Cornia et al., 2012; Jayne et al., 2010 in White, 2019).

ICTs are expanding, but capacity and use is highly variable. There is a major infrastructure deficit, for example the overall electricity access rate was only 11.2% in 2019 (4.1% in rural areas). While the mobile sector has grown rapidly, reaching over 90% mobile coverage in 2016, high taxes and prices have contributed to only 36.6 % of Malawians owning mobile devices (FAO and ITU, 2022).

3.4 Economic and market food system assets, trends and drivers

The economy is highly dependent on agriculture for exports (80-90%) and employment (77%), with agriculture contributing 26% of GDP in 2019 (http://wdi.worldbank.org). Agriculture is the main livelihood activity in Malawi (NSO, 2019).

Agricultural input markets are particularly geared towards the supply of hybrid maize seed and inorganic fertilizer. Postharvest inputs such as grain protectants are available, but affordability is an issue. Agricultural output markets are also geared towards maize for the domestic market. Tobacco accounts for 50% of all exports. Groundnuts are sold to domestic and regional markets, but aflatoxin risks destroyed their higher value export markets. Many policy advisors consider improving the performance of maize input and output markets essential for achieving food security in Africa (White, 2019).

Land tenure is a key but very complex and sensitive issue. Expansion of medium-sized farms is occurring in association with urban expansion and land acquisition by elites. There is uncertainty as to whether customary tenure reforms such as the Customary Land Act (2016) will hinder or further boost this development through privatisation of land rights and land market development (Holden, 2020).

3.5 Political and institutional food system assets, trends and drivers

While the government is responsible for setting public policy goals and targets, donors significantly influence policy design and implementation. Dominant narratives include i) food security being equated with maize consumption (Smale, 1995 in Sutcliffe et al., 2016), ii) the need to make agriculture climate resilient, iii) agriculture as part of a broader economic development focus (Chinsinga et al, 2012) and iv) the role of small-scale family farms, which is a long-standing policy debate.

Policy implementation, however, is dominated by agricultural input subsidies, mainly fertilizer and maize seed, aiming to bring about food self-sufficiency. Currently there is no subsidy on postharvest technologies, a subsidy on grain protectants was stopped in 2012 after just 2-3 seasons (Singano – Chitedze postharvest researcher - pers. comms.).

The Farm Input Subsidy Programme (FISP) used 50-75% of the agricultural budget, with mixed results and suspicions of graft (Schiesari et al., 2016; White, 2019). A new Agricultural Subsidy Programme introduced by the government in 2020, utilised 78% of the Ministry of Agriculture’s budget in the 2020/21 season. Funding of extension services has declined from 19% to <2% of the agricultural budget between 2000 and 2013 (Ragasa and Mazunda, 2018). The National Agriculture Policy (NAP) states “Malawi has over-concentrated on maize self-sufficiency for food” (MoAIWD, 2016), but the government continues to fund a maize-centred input subsidy programme. Many observers attribute this to lawmakers feeling they are politically bound to subsidies (Chinsinga and Poulton, 2014).

The NAP includes the policy statement “Reduce pre and postharvest losses and enhance quality of agricultural products”. However, it is not clear to what extent previous PHL management policy gaps in Malawi have been addressed, including policies being developed without a scientific evidence-base and not being harmonized, lack of climate-based scenarios for early warning systems and guidance; lack of monitoring and evaluation of implementation and effectiveness (Donga, 2014). Postharvest handling is missing from most Southern Africa Development Community (SADC) regional policies on managing climatic risk in climate disaster prone areas, and a need to facilitate stakeholder collective action and institutional coordination has been identified (Donga, 2014).

3.6 Socio-cultural food system assets and drivers

Maize in Malawi is imbued with cultural meanings that celebrate, enact, and reinforce local identity (Kampanje-Phiri, 2016). Maize is the preferred staple and commonly eaten as stiff porridge known as *nsima.* The centrality of maize to economic, social, and wellbeing is reflected in the Chewa maxim, '*Chimanga ndi moyo:* Maize is life' (White, 2019). Post-independence, from 1964 to 1994, President Banda, used maize-based food security as a means of exerting control, but in ways linked tightly to Malawian culture (Kampanje-Phiri, 2016; White, 2019).

Maize consumption accounts for three-quarters of the dietary energy, iron, and zinc availability and two-thirds of protein availability across both seasons. This reflects the large share of maize consumed relative to other foods in the diet. Maize, particularly in the form of maize flour, dominates collective perceptions of household food security. It is seen as a requirement, whereas other preferred food items may be viewed as luxuries (Gelli et al., 2019).

Gender inequality and a range of power imbalances have a profound impact on food systems and social and environmental outcomes in Malawi (Njuki et al., 2021; Bezner-Kerr et al., 2019).

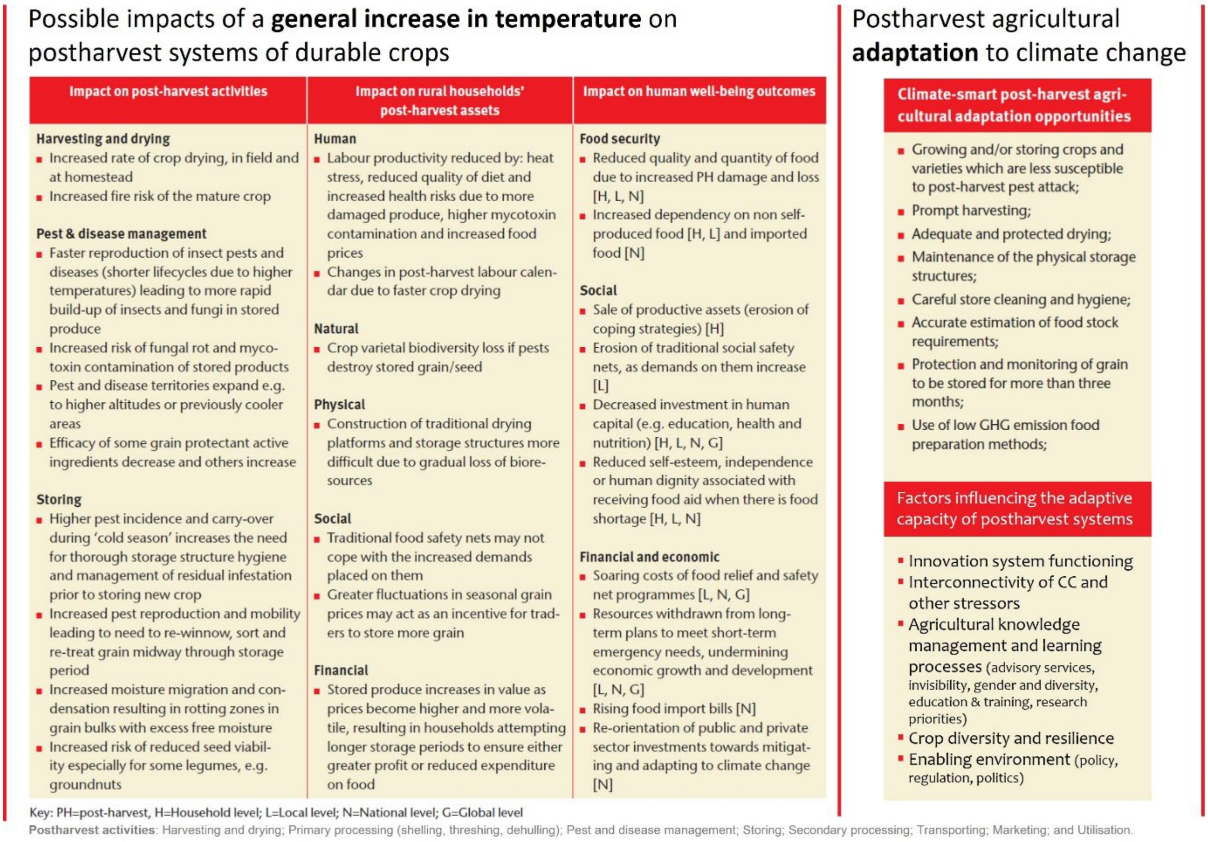
4. Environmental impacts on and of food loss and waste

4.1 Climate change impacts on postharvest aspects of food systems

Understanding and modelling the effects of climate change on biodiversity, agriculture and other ecosystem services has been the focus of extensive research. For agriculture, this focus has predominantly been on the preharvest stages, particularly projected impacts on yields, crop suitability and livelihoods. There has been limited consideration of the impacts on postharvest stages (Stathers et al., 2013; Adler et al., 2022; Gerken and Morrison, 2022).

This knowledge gap triggered a think-piece on postharvest agriculture in changing climates. Using five climate change trends relevant to different parts of SSA (general increase in temperature; more frequent occurrence of dry spells and droughts; more frequent occurrence of high winds, storms, heavy precipitation events and flooding; more erratic rainfall; increased rainfall amount and/or duration), Stathers et al. (2013) developed a framework to analyse the impacts on, adaptation opportunities for and factors influencing adaptive capacity of grain crop postharvest systems for the key postharvest activities, assets and associated human well-being outcomes.

The analysis for 'a general increase in temperature', highlights how this could lead to increased rates of crop drying in field and at the homestead, more rapid multiplication and build-up of insect pest populations in stored products, increased carryover of field and storage pests and disease between seasons etc. (Figure 4). It then envisages how these changes might impact postharvest assets of rural households. For example, what an increase in temperature might mean for labour productivity during harvest and threshing, what increased damage to home-stored seed might mean for locally adapted varieties and biodiversity, for traditional food safety nets and food price volatility. Then, how these impacts might affect human well-being outcomes. Might higher damage and losses to stored grain and seed result in reduced quantities and qualities of food? Might some households have to sell off productive assets to cope? Might some food environments shift from being predominantly self-cultivated and market-based towards greater dependency on non-market sources and food donations with increased food relief costs? To address these postharvest-related impacts, adaptation opportunities were identified. Many of which can be classified as 'no regrets' actions (justified whether natural hazard events or climate change take place or not), and are already well-known but not yet in use at scale. That led in to an analysis of what is needed to strengthen postharvest aspects of the agricultural innovation system to strengthen postharvest adaptive capacity. Understanding how complex systems adapt and transform is needed for developing climate resilience adaptation strategies (Nelson et al., 2007).



Possible impacts of a **general increase in temperature** on postharvest systems of durable crops

Impact on post-harvest activities	Impact on rural households' post-harvest assets	Impact on human well-being outcomes
Harvesting and drying ▪ Increased rate of crop drying, in field and at homestead ▪ Increased fire risk of the mature crop **Pest & disease management** ▪ Faster reproduction of insect pests and diseases (shorter lifecycles due to higher temperatures) leading to more rapid build-up of insects and fungi in stored produce ▪ Increased risk of fungal rot and mycotoxin contamination of stored products ▪ Pest and disease territories expand e.g. to higher altitudes or previously cooler areas ▪ Efficacy of some grain protectant active ingredients decrease and others increase **Storing** ▪ Higher pest incidence and carry-over during 'cold season' increases the need for thorough storage structure hygiene and management of residual infestation prior to storing new crop ▪ Increased pest reproduction and mobility leading to need to re-winnow, sort and re-treat grain midway through storage period ▪ Increased moisture migration and condensation resulting in rotting zones in grain bulks with excess free moisture ▪ Increased risk of reduced seed viability especially for some legumes, e.g. groundnuts	**Human** ▪ Labour productivity reduced by: heat stress, reduced quality of diet and increased health risks due to more damaged produce, higher mycotoxin contamination and increased food prices ▪ Changes in post-harvest labour calendar due to faster crop drying **Natural** ▪ Crop varietal biodiversity loss if pests destroy stored grain/seed **Physical** ▪ Construction of traditional drying platforms and storage structures more difficult due to gradual loss of bioresources **Social** ▪ Traditional food safety nets may not cope with the increased demands placed on them ▪ Greater fluctuations in seasonal grain prices may act as an incentive for traders to store more grain **Financial** ▪ Stored produce increases in value as prices become higher and more volatile, resulting in households attempting longer storage periods to ensure either greater profit or reduced expenditure on food	**Food security** ▪ Reduced quality and quantity of food due to increased PH damage and loss [H, L, N] ▪ Increased dependency on non self-produced food [H, L] and imported food [N] **Social** ▪ Sale of productive assets (erosion of coping strategies) [H] ▪ Erosion of traditional social safety nets, as demands on them increase [L] ▪ Decreased investment in human capital (e.g. education, health and nutrition) [H, L, N, G] ▪ Reduced self-esteem, independence or human dignity associated with receiving food aid when there is food shortage [H, L, N] **Financial and economic** ▪ Soaring costs of food relief and safety net programmes [L, N, G] ▪ Resources withdrawn from long-term plans to meet short-term emergency needs, undermining economic growth and development [L, N, G] ▪ Rising food import bills [N] ▪ Re-orientation of public and private sector investments towards mitigating and adapting to climate change [N]

Postharvest agricultural **adaptation** to climate change

Climate-smart post-harvest agricultural adaptation opportunities

- Growing and/or storing crops and varieties which are less susceptible to post-harvest pest attack;
- Prompt harvesting;
- Adequate and protected drying;
- Maintenance of the physical storage structures;
- Careful store cleaning and hygiene;
- Accurate estimation of food stock requirements;
- Protection and monitoring of grain to be stored for more than three months;
- Use of low GHG emission food preparation methods;

Factors influencing the adaptive capacity of postharvest systems

- Innovation system functioning
- Interconnectivity of CC and other stressors
- Agricultural knowledge management and learning processes (advisory services, invisibility, gender and diversity, education & training, research priorities)
- Crop diversity and resilience
- Enabling environment (policy, regulation, politics)

Key: PH=post-harvest, H=Household level; L=Local level; N=National level; G=Global level

Postharvest activities: Harvesting and drying; Primary processing (shelling, threshing, dehulling); Pest and disease management; Storing; Secondary processing; Transporting; Marketing; and Utilisation.

Figure 4 Possible impacts of 'a general increase in temperature' on grain postharvest systems and potential adaptation opportunities. Source: adapted from Stathers et al., 2013.

That think-piece spawned research in Malawi and Zimbabwe with smallholder farming communities' and their service providers. Participatory field studies explored climate impacts and linkages, identified postharvest management interventions effective in different agro-climatic conditions and approaches for strengthening learning and capacity around climate-resilient grain postharvest systems, alongside laboratory studies on the effects of warming on grain protection (Mlambo et al., 2017, 2018; Mubayiwa et al., 2018, 2021; Singano et al., 2019, 2020; Nyabako et al., 2020b).

Agro-climatic conditions also influence the growth of certain fungi on food crops such as maize and groundnuts to produce toxic secondary metabolites called mycotoxins. Consumption of mycotoxin-contaminated produce causes symptoms ranging from immune deficiency, stunting, organ failure, cancer, to death (Udomkun et al., 2017), and crop yields can be affected (Magan et al., 2011). Aflatoxin levels in on-farm stored maize samples collected from smallholder farmers in Malawi were on average higher in areas with a higher annual mean temperature, this trend was not observed for fumonisin (Ng'ambi et al., 2022). Climate change is expected to affect the geographic distribution, type, and concentration of mycotoxins (Paterson and Lima, 2010). Models are being developed to provide agro-climatic mycotoxin risk warnings to support more targeted monitoring (Keller et al., 2022). Using projected climate trends, Warnatzsch et al. (2020) modelled aflatoxin contamination risks for two varieties and three planting dates across Malawi. Their results suggest future climatic changes will shorten maize growing seasons leading to earlier harvesting for short and long maturity varieties and increased risk of pre-harvest aflatoxin B1 contamination in all regions of Malawi. Where drying or storage conditions are poor such fungi can continue growing and metabolizing toxins after harvest (Channaiah and Maier, 2014). Risks associated with increased aflatoxin contamination of maize in Malawi are heightened by limited knowledge regarding the impacts of consuming mouldy food (Bullerman and Bianchini, 2007; Matumba et al., 2016). Many farming households sell their best grain, while retaining the grain with highest probability of mycotoxin contamination for home consumption (Kimanya et al., 2008; Mwalwayo and Thole, 2016). This highlights the need for greater mycotoxin risk awareness alongside improved postharvest management practices and training (Warnatzsch et al., 2020; D. Miller pers. comms.).

Degraded natural environments, may offer less buffering (e.g., fewer natural enemies) against storage pests which infect the crop while still in the field, leading to more rapid build-up of pests. Deforestation may affect dispersal behaviour and in field and store population dynamics of storage pests such as the wood-boring larger grain borer (LGB), *Prostephanus truncatus* and rodents which also inhabits natural forests (Muatinte et al., 2014). A study in Mozambique, suggested trade in firewood (which increases during seasons when crops fail, and farmers employ alternative coping strategies) could be leading to dispersal of *P. truncatus* to previously uninfested areas (Muatinte and Van den Berg, 2019). Given that *P. truncatus* causes weight losses twice those of Sitophilus weevils and other common storage pests (Hodges et al., 1983), increased multiplication and geographical spread of the pest may significantly increase maize and cassava storage losses.

Deforestation links with increased local temperatures and wind which influence damage, deterioration and rotting of perishable fruits and vegetables at and after harvest. Links between deforestation, climate and drying up of local water holes lead to people having to walk further to find water or use more contaminated water sources – which will impact on the way households and SMEs process crops e.g., cassava.

Climate-related yield impacts affect food production, availability and sourcing. For example, cyclone-related flooding damaged crops, property and transport routes in Malawi leading to reduced food supply, alternative trading routes and higher food prices and a range of detrimental coping strategies in both rural and urban areas (Joshua et al., 2021).

4.2 The environmental footprints of food loss and waste – case study of maize in Malawi

Postharvest systems are both acted on by, and in turn impact on, the climate and the environment. Food production is a major cause of environmental degradation, contributing to climate change, biodiversity loss, freshwater use, land system change, interference with the global nitrogen and phosphorous cycles, and chemical pollution (Willet et al., 2019).

Using maize in Malawi as a case study, we combined existing datasets to explore the environmental footprints of the maize that is lost within the food system. This involved understanding the quantities and causes of food being lost (at and after harvest through to the wholesale marketing) or wasted (by retailers, caterers, or consumers). This is challenging because: a) losses vary by postharvest activity, location, handling practice and technology, and storage duration etc. and b) food that is 'lost' is often never actually collected, seen or counted, which means farmers' or other actors' perceptions of loss should be treated with some caution.

4.2.1 Quantifying the postharvest food loss

The 2007/08 food price crisis led to demands for a more nuanced understanding of the scale and location of staple food PHLs in different provinces/regions of SSA countries. In response, the African Postharvest Losses Information System (APHLIS www.aphlis.net) was developed in 2009.

The APHLIS uses high quality measured PHL data to build a loss profile for each crop and activity/value chain stage, and then contextualises the loss figure using locally-specific factors such as proportion marketed straight after harvest, storage duration, pest incidence, rain around harvest occurrence etc.. The quantity lost in each province is determined by combining the percentage loss estimate with subnational-level production data. Price, food composition and demographic data are used to provide an indication of the financial and nutritional values and impacts of the loss.

About 19% of Malawi's 3.29 million tonnes of maize produced annually (average figure for 2018-2020) is estimated to be lost postharvest (Figure 5). A loss of over 600,000 tonnes of grain a year, worth USD158 million and equivalent to the annual dietary energy (kcal) requirements of 2.6 million people (APHLIS, 2021). Loss hotspot activities include harvesting and field drying (loss of 6.3% of the potential yield), further drying (4% of remaining crop lost), and household-level storage (8.5% of the stored crop gets lost) (Figure 5). Many African countries experience similar substantial proportions of maize lost.

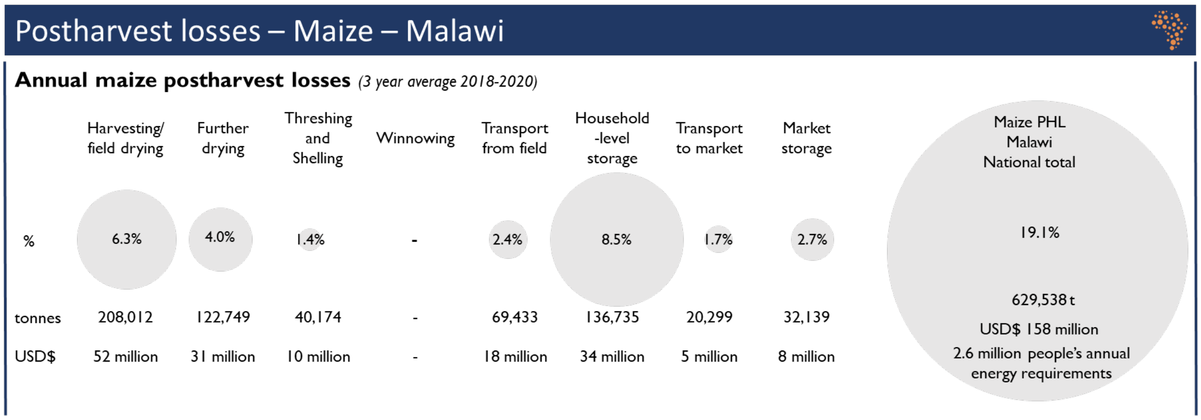


Figure 5 Estimates of maize losses occurring at different value chain stages at and after harvest in Malawi, by percentage, tonnes, USD and number of people's annual dietary energy requirements. Source: APHLIS, 2021 (PHL data) and Malawi Ministry of Agriculture, Irrigation and Water Development (production data).

4.2.2 Assessing the environmental footprint

A range of resources are used producing and handling food crops which are then lost at and after harvest.

Land footprint: The land footprint, or area of land used to produce maize that is then lost at or after harvesting, can be calculated by dividing the tonnes of maize lost postharvest by the yield (t/ha). Continuing the Malawi example, a total of 330,114 ha of land (equivalent to ~175 m^2/capita/year) was tilled, planted and weeded to produce maize that was then lost postharvest.

Water footprint: Water footprints can help understand the water-related roles, dependency, trends and drivers in an economy, and help make visible the water resources hidden in different products that are used, traded, or lost. From a water resource perspective, irrigated agriculture has a larger environmental impact than rain-fed, as it may lead to water depletion, salinization, water-logging or soil degradation (Aldaya et al., 2010; FAO, 2013).

Mekonnen and Hoekstra (2011, 2014) modelled crop water use over time, climatic conditions and soil water balance to create a subnational level dataset for 126 crops and their products. This dataset was used to compare the water footprints for different crops and districts in Malawi (supplementary Figure S3). High yielding systems or crops or those where a larger fraction of their biomass is harvested, generally have smaller water footprints per tonne (e.g., starchy root crops) than lower yielding crops or those where a smaller fraction of crop biomass is harvested (e.g., cereals, oilcrops) (FAO, 2013).

Multiplying Malawi’s mean maize water footprint (3,758 m^3/tonne) by the tonnes of maize lost postharvest, reveals that the maize lost postharvest has an annual water footprint of 2.37 billion m^3 (127 m^3/capita/year), the subnational figures are also shown in Figure 6.

The global average maize water footprint is 1,028m^3 per tonne (supplementary Figure S3), while Malawi’s is 3,758 m^3 per tonne, and other African countries are similar. Malawi’s maize water footprint is relatively high because yields are relatively low, highlighting the need to increase maize water efficiency through sustainable management practices, e.g., improved soil management and nutrition during crop production, and improved postharvest handling to reduce losses. Changes to the cropping system could also reduce the agricultural water footprint.

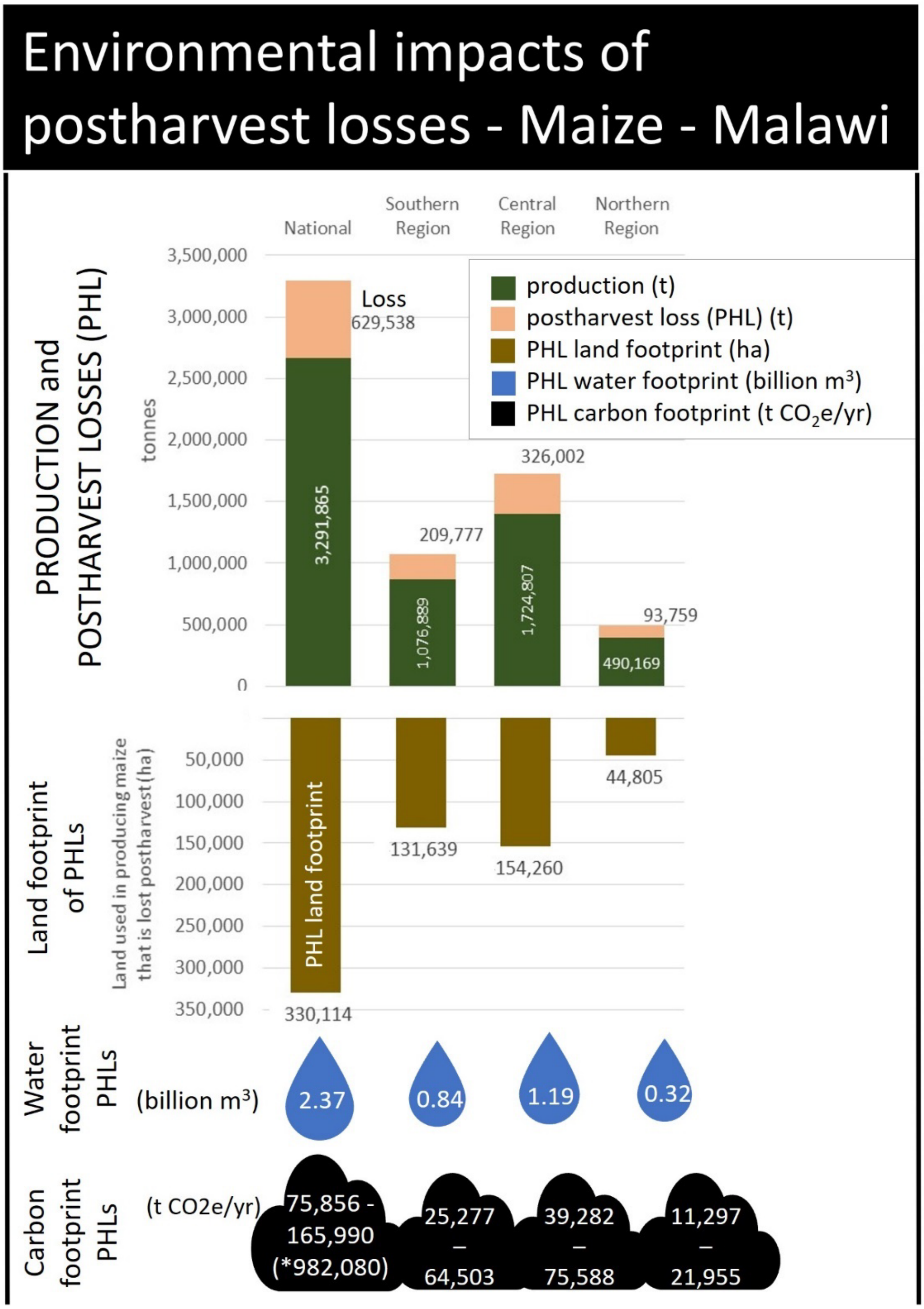


Figure 6 Land, water and carbon footprints of annual maize postharvest losses in Malawi (2018-2020)

Carbon footprint: The carbon footprint of a food reflects the total amount of GHG emissions occurring during the production, transportation, storage, processing, distribution, cooking, consumption and waste disposal of it. While land and water footprints of food are typically concentrated at the primary production stage (although water use may occur during processing), GHG emissions typically accumulate along the value chain. The GHG emissions per unit of food lost or wasted are therefore higher towards the retail and consumption stages (FAO, 2019).

In the mainly rain-fed, non-mechanised smallholder maize farming systems common in many SSA countries, the largest GHG emissions factor is typically associated with application of synthetic nitrogen fertilisers (Ba, 2016), if they are used. The high emissions footprint of fertiliser, results from a) production and manufacturing of fertiliser, b) transport to and within Africa, particularly in land locked countries, and c) field application (during and after). Therefore, the type of fertiliser used, the application rate and local agro-ecological conditions (Wang et al., 2017; White, 2019)all influence the carbon footprint of maize production and any associated losses. A West African study found fertiliser application contributed 88% of total emissions in maize farming in Cote d'Ivoire, and these emissions would have increased by 63% were the nationally 'recommended' fertiliser application rates practiced (Ba, 2016). In Benin, small amounts of emissions also occurred from burning fuel to operate farm machinery and equipment, and crop residue burning. Among nitrogen fertilisers, urea has lower GHG emissions associated with its production, but higher emissions in the field (Fossum, 2014). Optimising crop management and nutrient use efficiency by adjusting the use and type of (Wang et al., 2017) nitrogen fertiliser can reduce GHG emissions directly on the field and indirectly through reduced manufacture and transport (Peter et al., 2017). Improving road freight transport efficiency can also offer high emissions reduction potential (Thambiran and Diab, (2011) in White, 2019).

GHG emissions factor values for maize across SSA range from 0.1385 to 1.56 t CO_2e/t (see FAO, 2017 (LEAP database); Ba, 2016; Broeze et al., 2019; Porter et al., 2016, Vetter et al., 2017), reflecting assumptions around how much fertiliser was applied, and the chosen boundaries of each specific life cycle analysis, e.g., whether they start from fertiliser production, and which value chain stages they include. High levels of uncertainty around GHG emission predictions by these calculators exist due to their inability to account for differences in pedoclimatic conditions, agricultural management practices and crop rotations (Peter et al., 2017). There are additional uncertainties around land use changes and field emissions from different fertiliser types and crop residues, and many agricultural processes, which depend heavily on local biophysical and climate conditions, are not well understood (Cherubini and Stromman, 2011).

We compared the PHL carbon footprint for Malawi using the range of emissions factors available in the literature. We used the ACGE (Agro-Chain Greenhouse Gas Emissions) interactive calculator developed by Broeze (2019) which recognises the different postharvest activities and allows customisation by users. For example, the ACGE allows users to enter/select: a) a case specific GHG emissions factor, b) specific percentage loss values for each postharvest stage (enabling us to enter the Malawi maize PHL values from APHLIS), c) options depending on grain transport distances and means (motorised or non-motorised), whether harvested mechanically or manually, whether crop residues were left on field, and d) the energy type and packaging materials if processing stages are included etc.

Given the influence of fertiliser type and application rate in determining the GHG emissions factor, we searched the literature for smallholder farmer maize fertiliser recommendations and practices in

Malawi. Using these, we calculated the associated t CO_2e/ha emission factor values and using the PHL land footprint calculated the carbon footprints. The range of carbon footprints for Malawi's maize losses emerging from these different emissions factors are shown in Table 1 and Figure 6. At national level - using the lowest emission factor of 0.1385kg CO_2e/kg DM (FAO LEAP, 2017) and a higher emission factor of 0.49t CO_2/ha based on fertiliser recommendations (and 0.64 t CO_2/ha for the portion of the lost crop that had been transported to market) - emissions range from 75,856 to 165,990 t CO_2e/year and per capita from 0.0041 to 0.0089 t CO_2e/year. Use of the much higher SSA-wide maize emission value factor of 1.56 t CO_2e/t from Porter et al., 2016 would result in a figure of 982,080 t CO_2e/year. As discussed, the high level of uncertainty around these emissions and emissions factors needs noting. Additional uncertainties exist around land use change and maize production in Malawi. The scarcity of land suggests most maize production occurs on land previously used for crop production. Most recent land conversions (2010-2019) were reportedly from grasslands as opposed to forests, although between 2001 and 2018 cropland expansion accounted for 31% of forest loss, but a declining trend was reported (Li et al., 2021).

Analysis of the biodiversity footprint was beyond the scope of this study.

Table 1 Maize production, postharvest losses and environmental impacts of postharvest losses at national and subnational levels in Malawi and by value chain stage

Level	**National**	**National**	**National**	**National**	**National**	**National**	**National**	**National**	**National**	**Southern Region**	**Central Region**	**Northern Region**
Value Chain stage	Harvest to Market storage	Harvesting/ field drying	Further drying	Threshing and Shelling	Winnowing	Transport from field	Household-level storage	Transport to market	Market storage	Harvest to Market storage	Harvest to Market storage	Harvest to Market storage
Area harvested (ha)	1,726,170									675,770	816,158	234,241
Production (t)	3,291,865									1,076,889	1,724,807	490,169
Postharvest losses												
PHL%	19.1	6.3	4.0	1.4	-	2.4	8.5	1.7	2.7	19.5	18.9	19.1
PHL (tonnes)	629,538	208,012	122,749	40,174	-	69,433	136,735	20,299	32,138	209,777	326,002	93,759
PHL Financial value (USD)	158,436,989	52,343,514	30,889,561	10,110,880	-	17,470,408	34,440,323	5,103,199	8,079,196	53,538,580	81,689,367	23,208,982
PHL Nutrients: equivalent number of people's annual dietary energy (Kcal)	2,624,515									874,550	1,359,088	390,875
Environmental footprints												
PHL Land footprint (ha)	330,114	109,076	64,366	21,066		36,409	71,700	10,644	16,852	131,639	154,260	44,805
PHL Water footprint (green + blue) footprint (billion m^3)	2.37	0.78	0.46	0.15		0.26	0.51	0.08	0.12	0.84	1.19	0.32
Carbon (CO_2 eq tonnes/year) (range)	75,856 - 165,990	25,064 - 53,477	14,791 - 27,677	4,841 - 10,322		8,366 - 17,840	16,476 - 35,133	2,446 - 6,855	3,872 - 10,853	25,277 - 64,503	39,282 - 75,588	11,297 - 21,955

4.3 Opportunities for reducing food loss and waste and the associated environmental impacts

Numerous opportunities to reduce these PHLs and their associated environmental impacts exist. A recent systematic review synthesised all the evidence from the last 50 years on interventions small-scale farmers and their associated value chain actors in SSA or South Asia could use to reduce losses for 22 food crops (Stathers et al., 2020). That synthesis aimed to capture the diverse range of interventions that had been tested including policy, finance, infrastructure and training interventions. However, it revealed the dearth of evidence about such types of interventions. Almost all (90%) of the loss reduction research to date has been on tangible technology-type interventions particularly targeting loss reduction during storage and for cereals, especially maize.

While many of the technologies identified can reduce losses, it is also the case that whether a cool storage unit with different energy source options, or polypropylene or hermetic sacks, they all have emissions footprints. This highlights the need to understand the environmental benefits (i.e., the environmental footprint reduction associated with the loss reduction) and whether they outweigh the environmental costs (i.e., environmental impacts of fabricating, transporting and using the intervention). A small but growing body of work is analysing this (Boxes 1 and 2).

Box 1. Comparing maize storage protection options

Dijkink et al., (2019) compared African smallholder farmers' maize losses during storage in double lined hermetic bags versus standard polypropylene bags with and without pesticide application and the associated GHG emissions. The emissions related to the hermetic bag packaging was significantly smaller than the impacts related to the maize losses which would occur in the absence of storage in a hermetic bag. Therefore, for maize storage durations beyond 30 days, use of hermetic bags contributed to a net reduction of GHG emissions per unit of maize marketed for consumption. However, economically, when maize is stored for own consumption, polypropylene bags gave higher returns until ≥ 100-149 days storage duration, at which point hermetic bags became preferable economically. Where higher seasonal price fluctuations occur, hermetic bags can be profitable for maize stored for ≥ 50 days duration.

Designing interventions that minimise trade-offs between different environmental -alongside social and economic - impacts is key (FAO, 2019). Packaging is often associated with high environmental footprints in the food system, but the benefits packaging brings in terms of reducing food loss and waste - particularly for products with heavy production stage environmental footprints - and in logistical efficiency, also need to be considered in packaging life cycle assessments (Molina-Besch et al., 2019). Significant work around optimising packaging performance and sustainable packaging materials is occurring.

Box 2. Using cooler temperatures to reduce food loss and waste

A Swedish study (Eriksson et al., 2016) explored whether the benefits of reduced cheese, dairy and meat product waste in six supermarkets exceeded the increased energy costs of maintaining colder storage temperatures. Increasing net savings in GHG emissions and money occurred for meat products, but not for dairy and cheese products. Net benefits were only achieved for products with high relative waste, low turnover and high value per unit mass.

An analysis of the additional refrigerant and energy impacts versus food loss reduction related GHG emissions for cold-chain introduction in SSA highlighted further complexities (Heard and Miller, 2019). These include anticipated impacts of cold chain transformations on the upstream supply chain and on dietary shifts related to improved access to perishable foods, which may be more environmentally-intensive to produce (Garnett, 2007). This underscores the need to consider indirect and external factors associated with technologies such as cold or cool chains - often viewed as a hallmark of a modern food system - alongside the direct environmental impacts (Heard and Miller, 2016; Miller and Keoleian, 2015). The analysis calculated that adding refrigeration to SSA would increase net food-related GHG emissions by 10% from the baseline to a North American scenario and by 2% to a European scenario, despite reducing food PHLs by 23% in both scenarios (Heard and Miller, 2019). The GCCA Global Cold Storage Capacity report (IARW, 2020) contains data for a few SSA countries (Table 2). It highlights a) the current low levels of cold storage capacity and b) the difference between cold chain emissions added and those avoided due to reduced losses differing by food and energy type and scenario. Various mechanisms for reducing cold or cool chain emissions exist, including through more energy efficient refrigeration technologies and use of solar powered units (James and James, 2010; Kitinoja, 2013). However, increasing ambient temperatures may lead to potential emissions increases, and in much of SSA existing high ambient temperatures will influence the efficiency and emissions of cold chain operation (James and James, 2010). A sole focus on changes in GHG emissions associated with food loss reduction interventions such as cold or cool chains or hermetic bags, ignores important societal benefits, i.e., food and nutrition security, health outcomes, economic development. However, there has been limited study of the socio-economic or environmental outcomes of food loss reduction interventions in SSA to date (Stathers et al., 2020).

Table 2 Refrigerated Warehouse Capacity by Country, 2020 (Source: IARW, 2020)

	Ethiopia	Ghana	Kenya	Nigeria*	Rwanda	South Africa	Uganda	India	UK	US
Million m^3	0.12	<0.001	0.55	0.001	0.0193	2.71	0.06	150	35.93	156.21
m^3 per urban resident	0.005	<0.005	0.038	0.002	0.009	0.069	0.005	0.328	0.644	0.577

* Nigeria data is for 2018, not 2020

5. Informing FLW reduction decision-making in a food systems context

The complexity of the data, the uncertainties, options and potential economic, social and environmental trade-offs / synergies associated with decision-making around FLW reduction is clear. Exploring this complexity in ways which can inform decision-makers is important. With so many important gaps in current knowledge, more emphasis needs to be placed on coordinated learning, especially assessment of whether PHL remediation investments are relatively cost-effective in advancing the four core objectives that motivate such initiatives: improved food security, food safety, and profitability, as well as reduced resource use (Sheahan and Barrett, 2017).

5.1 Why the wider food system matters for FLW

As food systems across SSA transition to meet the changing dietary demands of populations - that are growing, urbanising, and progressively characterised by expanding youthful as well as middle class consumers - increased volumes of food will be traded and possibly lost or wasted. Research suggests the share of ‘imported’ food in the rapidly growing urban middle-class diet will not rise, instead more meat and locally produced, often perishable products (e.g., fresh fruits, fish and eggs), start to be eaten (Tschirley et al., 2015). The design of urban areas affects many aspects of the food system and needs greater study (Seto and Ramankutty, 2016).

Increased processing and packaging of food is likely, and retail, hospitality and consumer level food waste may increase if trajectories mirror those that have occurred in other geographical regions. To date, limited work measuring food waste at consumer, hospitality and retailer levels in SSA has occurred. Two studies in South Africa reported contrasting per capita annual food waste of 8-16 kg and 73 kg (Chakona and Shackleton, 2017; Ramukhwatho et al., 2018, Stathers and Mvumi, 2020). A questionnaire survey in Burkina Faso, Senegal and Ghana found a third of rural households reported wasting 3-18 adult portions a month (Loada et al., 2015). A detailed waste analysis within Ghana found an average of 84 kg/capita/year (edible and inedible) food waste, but it varied by location (44kg/capita/yr in Savannah areas to 131kg/capita/yr in Coastal areas) (Miezah et al., 2015). A study in Kigali obtained high self-reported estimates of retail and restaurant level food waste quantities (Nishimwe, 2020). More work using measurement methods that support comparisons is needed, including around how food waste varies with socio-cultural and agro-ecological factors. The suggestion that food waste is much lower and food loss much higher in low income compared to high-income countries, is being challenged by the few measured studies that have occurred (Johnson et al., 2018; Stathers and Mvumi, 2020; UNEP, 2021).

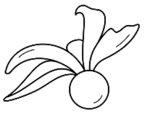
At the food system level, it is also important to consider trends and drivers and different scenarios for future systems. The dominant narrative around transitioning food systems and nutrition, much like the modernisation narrative to which it is related, assumes relatively universal food system development trajectories regardless of historical or material conditions. Such assumptions remove the impetus to examine local food exchange and provisioning practices, rendering them invisible and under-researched (Meagher, 2018 in White, 2019).

There is increasing interest by some actors in various interpretations of agroecology and transformation of food systems (HLPE, 2019). Agroecology has been described as a science, practice, and social/ political movement (Wezel et al., 2009). It has also been considered at different scales from field, farm, agroecosystem to food system (Gliessman, 2016). Agroecological principles (HLPE, 2019) and elements (FAO, 2018) have been developed to support diverse pathways for incremental and transformational change towards more sustainable farming and food systems (Wezel et al., 2020). However, little consideration of what these might mean for FLW and postharvest management has occurred. Examples from the few disparate but interesting studies on how production systems influence FLW are shared in Box 3.

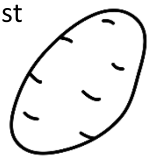
Box 3. Do different types of production systems influence FLW?

How different types of production systems (e.g., agroecological vs. conventional) influence FLW is not well understood. A few studies comparing FLW under different production systems are summarised below.

Vegetables and salads: Baker et al. (2019) suggest that by taking a food system approach that accounts for yields as well as loss and waste in distribution and consumption, the contribution of different food systems to food security can be compared. They use a novel concept of “net yield efficiency” (NYE) and compare levels of fresh vegetable and salad waste in the supermarket-controlled food system with a community supported agriculture (CSA) scheme. They found when all stages of the food system were measured for waste, the CSA dramatically outperformed the supermarket system, wasting only 6.7% by weight compared to 40.7–47.7%.



Cape gooseberry: Higher sensitivity to postharvest deterioration was observed to occur in cape gooseberry fruits obtained through agroecological as opposed to conventional production in Colombia (Collazos et al., 2019).



Potato: In non-organic and organic potato supply chains in Switzerland, losses at harvest were measured and losses at later stages were estimated by stakeholders. For fresh potatoes, total losses of non-organic potatoes were 53%, and 56% for organic. For processing potatoes, they were slightly lower at 46% (non-organic) and 41% (organic) (Willersinn et al., 2015) (Table 3). Less loss due to overproduction occurred in the organic potato supply chain. Overproduction of potato is associated with the unpredictability of production, and the price elasticity of demand for organic is higher than non-organic potatoes in high supply years (Bunte et al., 2007). For organic potato, farm stage losses were predominantly quality driven as opposed to quality and overproduction factors as seen in non-organic potato. Higher quality losses in organic potatoes are presumably due to reduced chemical use and varietal differences. Wholesale and processing losses differ by intended product, e.g., chip production requires particular potato size and variety specifications and is associated with high losses. While processors involved in a diversity of multi-potato-products can recycle chip throwouts/losses to produce mashed potato products etc. When asked if quality specifications were lowered to reduce percentage losses at harvest, wholesalers, processors and retailers thought this would lead to increased amounts of technologically, institutionally and socially-driven losses at later supply chain stages (Willersinn et al., 2015). Currently more than 66% (non-organic) and 75% (organic) of fresh potato losses occur due to social drivers, particularly around aesthetic standards by consumers and their preferences for peeled potatoes (supplementary Figure S4).

Table 3 Comparative mean food loss rates at each stage of the organic and non-organic fresh and processing potato supply chains (in %) in Switzerland (Source: Willersinn et al., 2015)

	Fresh potatoes		**Processing potatoes**	
Cause of loss	**Non-organic**	**Organic**	**Non-organic**	**Organic**
Quality	25.7	34.8	21.9	23.3
Overproduction	9.1	1.0	7.9	0.4
Storage and transportation	1.9	2.6	3.8	4.7
Peeling while processing	0	0	10.1	10.9
Miscalculation	1.0	2.5	0	0
Raw potato losses in households	5.3	5.0	0	0
Peeling and preparation in households	8.2	7.7	0	0
Leftovers	1.9	1.8	2.0	2.1
Total	**53.0**	**55.5**	**45.6**	**41.3**

There is also increasing interest in more diversified systems (including as part of an agroecological approach). In Malawi, this could mean diversifying beyond maize which is very vulnerable to climatic change in both the production and postharvest stages to include other staple energy sources such as cassava, which is resilient in the production stage, but more vulnerable postharvest (Lamboll and Stathers, in prep.). A move towards more agroecological systems could include greater incorporation of grain legumes in production systems (Mhango et al., 2013, Madsen et al., 2021). Legumes need fewer inputs per kg of protein produced than animal protein and fix nitrogen enabling reduced or no nitrogen fertiliser application with lowered emission factors of the crops produced and any that are later lost (FAO, 2013). Legume crops can suffer heavy PHLs, particularly during storage if not protected from attack by storage insect pests. Like most interventions, legume integration would not be a one-size-fits-all solution and farmer-participatory research is required (Smith et al., 2016).

Potential trade-offs and synergies exist between FLW reduction and food system resilience including the contribution of over-production and over-supply to the generation of FLW while also providing resilience in the food system in the form of ‘redundancy’. Some FLW-reduction interventions may carry a risk of trade-offs due to loss of redundancy. But there are synergistic elements that support short and long-term resilience. For example, improved storage reduces the need for a constant flow of ‘surplus food’, replacing it with a stock of ‘spare’ food (Bajželj et al., 2020).

5.2 Informing FLW reduction decision-making in a food systems context

Understanding FLW in the context of the complexity of transitioning food systems is important. Decision-making around FLW reduction differs by location, scale/level, supply chain stage and the actors involved. The evidence on FLW in the wider food system context in SSA countries is very incomplete, particularly regarding FLW beyond the farm level and for non-cereal crops. Intersecting uncertainties around future conditions and responses (e.g., rainfall projections, indirect societal agri-food system responses to climate and other drivers of change, adoption of loss reduction interventions) add further complexity regards FLW projections and decisions. The Ceres2030 systematic scoping review found virtually no scientific evidence on how policy, infrastructure, training, finance or market interventions affect FLW in SSA and South Asia. The FLW research has been dominated by comparing the efficacy of technology/ equipment type interventions (Stathers et al., 2020). The focus to date has also been predominantly on the technical outcomes of these interventions with limited end-user involvement as opposed to analysing the social, economic or environmental outcomes of different FLW reduction interventions.

Despite broad agreement on the need to reduce FLW, considerable knowledge gaps clearly exist. Cattaneo et al. (2021) challenge researchers, policymakers and practitioners to address these through: (i) measuring and monitoring FLW, (ii) assessing the benefits, costs and trade-offs of FLW reduction, (iii) designing FLW-related policies and interventions under limited information, (iv) understanding how interactions between stages along food value chains and across countries affect outcomes of FLW reduction efforts, (v) preparing for income transitions and the shifting relative importance of losses and waste as economies develop.

Deeper understanding around assessing trade-offs and synergies relating to FLW and food systems changes and responses and outcomes by/ for diverse food system stakeholders at different levels is needed. Although reducing FLW has clear public good benefits, for individual stakeholders the private good may be less clear (Sheahan and Barrett, 2017). While FLW is a big environmental issue, whether it is also a financial, social or economic issue for particular stakeholders will vary with context as will the costs, benefits and incentives for FLW reduction. A lack of, or undervaluing of, the social and environmental externalities/ true costs of the food system may also be leading to excess

FLW (World Bank, 2020). Better understanding of this and of socio-techno-ecologically optimal levels of FLW - incorporating analysis of the direct and indirect drivers and the scale and impacts of the avoided FLW vs. the added environmental and other impacts of the intervention itself, and how different social groups are affected (Figure 7) - will inform how incentives and regulations could change to align public and private FLW reduction interests.

A preliminary framework for assessing trade-offs and supporting decision-making around FLW reduction interventions is shown in Figure 7. The final approach would be adapted according to context, but broadly involves the following:

1. Identifying the key focal food system(s) and within this the FLW focus (B).
2. Analysing the key drivers (A) influencing the system, as well as the direct causes (part of B).
3. Assessing the losses, associated stakeholders and direct causes at the focal postharvest activity stage (C) and the subsequent environmental footprints (D).
4. Exploring and understanding the effects on capitals and outcomes (E) and the relationship between these and the drivers (A) and the FLW (B & C).
5. Projecting future trends for these drivers over different timeframes.
6. Identifying intervention options based on the above analysis.
7. With key stakeholders (*to varying degrees stakeholders should be involved as early as possible in the whole process*) assess and prioritise the interventions based on a) minimizing trade-offs and maximising synergies between environmental footprint and the effects on capitals and outcomes, and b) monetary cost and implementation viability.
8. Establish and facilitate a multi-stakeholder social learning process with the aim of co-designing and implementing the selected interventions and then consistently improving the system.

Different locations will have different environmental priorities. If the FLW reduction aims to address water scarcity then the intervention should target cereals and legumes at the farmer-managed stages followed by fruits and vegetables (FAO, 2019). Whereas if the objective is reducing GHG emissions, then the greatest impact per unit of FLW avoided would be through targeting consumption stages (FAO, 2019). Given the knowledge gaps and the need for action, an appropriate balance between collection of FLW-related evidence and capacity strengthening of food system stakeholders is required to support FLW-related behavioural changes and deliver improved food system sustainability.

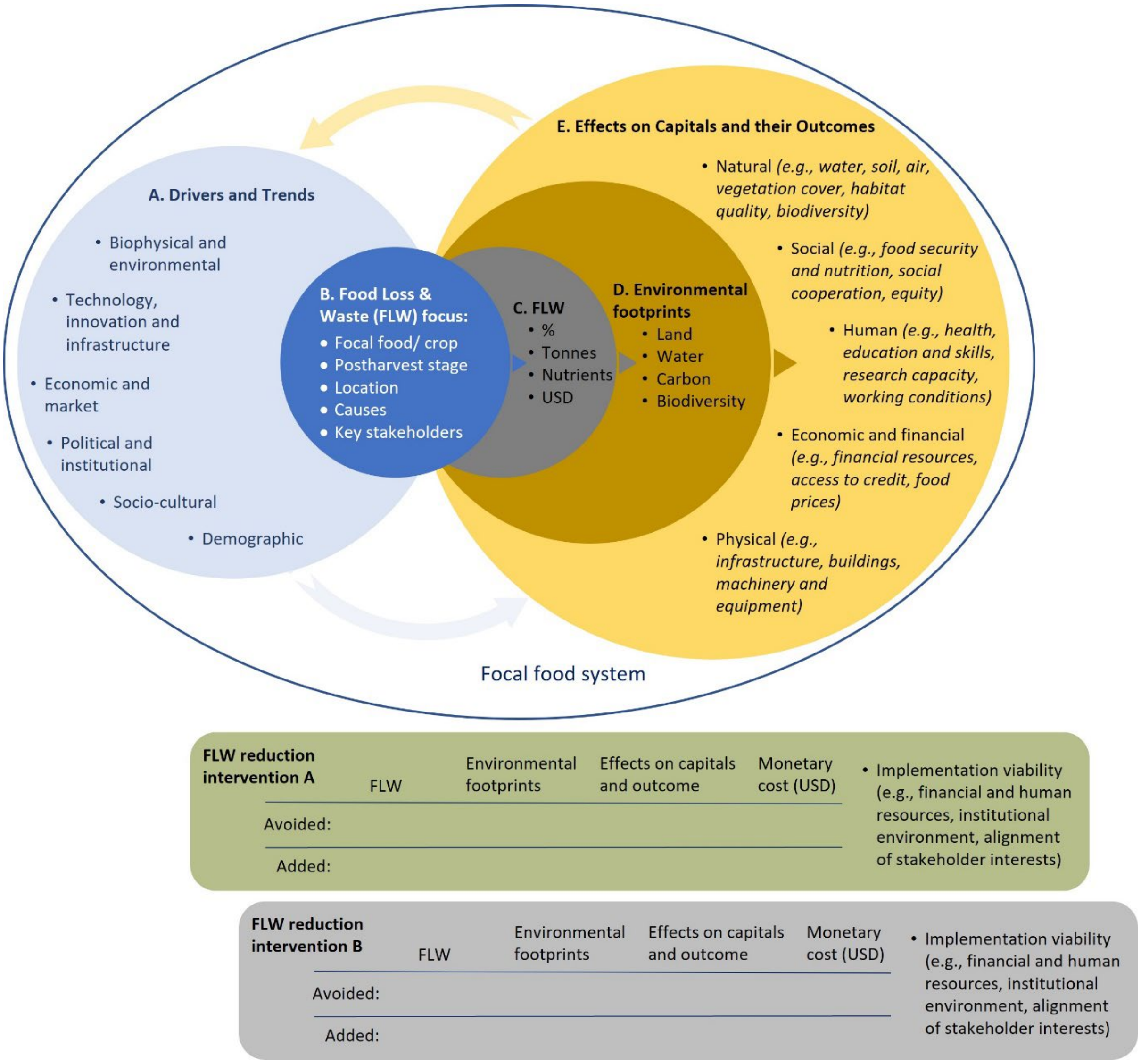


Figure 7 Preliminary framework for assessing trade-offs and synergies and supporting decision-making around FLW reduction interventions

6. Conclusions

Food systems will continue to transition in response to multiple drivers. Awareness is growing about the negative impacts of our food systems on the environment and the multiple challenges around ensuring a sufficient and more equitable supply of healthy food in the face of interlinked and interacting challenges including climatic change, natural resource degradation, population growth, changing dietary demands, and disease and conflict shocks. Our calculations of the land, water and carbon footprints associated with the maize that is lost in Malawi (alongside the existing financial and nutritional values) start to quantify the scale of the associated environmental impacts, helping to inform decisions and choices around the cost of action and of inaction. Reducing FLW clearly has the potential to bring environmental benefits, but only if the other drivers influencing the food system are aligned to do so. We need to ask whose values are -and whose should - shape food systems, who benefits and who bears the costs.

Society needs to consider what kind of food system would be both desirable and needed to keep within planetary boundaries for the future. This includes taking FLW issues into consideration as they and their management influence other parts of the food system, and thus the natural environment, human well-being, livelihoods and economies. It includes measurement of the scale of and recognition of all the causes of FLW, from practices, knowledge gaps, climatic factors, pests and diseases through to overproduction, market forces and aesthetic specifications. It requires recognition of the various dependencies in systems and how they may inhibit shifts and change, and increased awareness of the environmental, social and economic outcomes and opportunities.

Given the complexity and trade-offs, what type of research and evidence is required to inform action? While FLW-related research is increasing, is it aligned to what is needed, and are research and innovation processes aligned with appropriate food system stakeholders' decision-making processes? Participatory field testing of our preliminary framework for supporting decision-makers in assessing food system and FLW-reduction trade-offs and interventions could encourage more effective stakeholder engagement in the shaping and ownership of FLW-research and innovation processes. This is needed to drive better co-operation, commitment and trust within the whole supply chain and wider food system for healthier and sustainable outcomes.

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