Global Food Security 36 (2023) 100669

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Perspective: What might it cost to reconfigure food systems?

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ARTICLE INFO

Keywords:
Food system
Adaptation
Mitigation
Cost
Reconfiguration

ABSTRACT

Even an approximate estimate of the amount of investment required globally to reconfigure food systems for resilience and sustainability in the face of climate change could help to catalyse the urgent action that is needed. A report published in 2020 set out eleven actions that were identified as being needed to reconfigure food systems. Here we estimate the annual cost of implementing these eleven actions to be USD 1.3 ± 0.1 trillion. Half of this is needed to halt conversion of forests and peatlands for agriculture, with the remainder used to reduce producer risk, lower emissions and strengthen the policy, finance and innovation enablers of change. This cost, though large, is equivalent to less than 7 percent of the negative externalities generated annually by current food systems. The costs of inaction will far outweigh the benefits.

1. Introduction

More than 20 reports have been published in recent years on the need for transforming our food systems in the light of the challenges we face (see Pharo et al. (2019), GCA (2019), HLPE (2020), Global Panel on Agriculture and Food Systems for Nutrition (2020), and Rockefeller Foundation (2021), among others). Nevertheless, there is very little information on the size of the investments that would be needed, if the recommendations from such reports were to be implemented. In a previous "perspective" piece, Loboguerrero et al. (2020) summarised the high-priority actions that were laid out in the report of Steiner et al. (2020) on reconfiguring our food systems.

Steiner set out four key Action Areas necessary for food system reconfiguration:

(1) Rerouting farming and rural livelihoods to new trajectories that conserve ecosystems and the natural resource base, reduce social inequality, and provide food and nutrition security for all.
(2) De-risking livelihoods, farms and value chains, allowing food system actors to anticipate, respond to, and recover from increasingly frequent and extreme weather events.
(3) Producing, processing, distributing and consuming food in ways that lower greenhouse gas emissions and reduce food loss and waste.
(4) Realigning policies, finance, support to social movements, and innovation systems, to make this all happen.

Eleven concrete actions under these four Action Areas were identified (shown in Table 1) through consultations with over 100 partners, individuals and organisations and through a series of background science papers, detailed in Steiner et al. (2020). These actions address various players in the food system: for example, food processors, through helping to reduce food loss and waste; consumers, through moving to healthier, more climate-friendly diets; and national food policy makers, through actions that foster innovation and sustainable finance. Several of the actions target farmers explicitly: adopting climate-smart practices and utilising digital climate services for helping to make better management decisions, for example. Globally, food producers are clearly going to be a large part of the solution to the challenge of food system reconfiguration. At the same time, we recognise that the eleven Steiner actions are not all-encompassing, but they do represent a reasonable, partner-based estimate of what is needed to provide the necessary momentum for systemic reconfiguration to occur.

In the next section, we outline the information sources and the proxies that we used to estimate the annual cost of each action, given that some of the actions are very difficult to cost directly. We stress that what follows is not an economic investment analysis but a simple cost accounting exercise. We present the results of this exercise and then discuss what they may imply in a development context.

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https://doi.org/10.1016/j.gfs.2022.100669
Received 4 August 2022; Received in revised form 12 December 2022; Accepted 13 December 2022
Available online 26 December 2022

2. Costs of implementing each action

A preliminary review was undertaken of more than 2000 peer-reviewed articles, working papers, investment platforms, governmental documents, private sector reports, open data sources, news releases, budget estimations and financial reports. We identified 321 sources that provided potentially relevant cost data in relative to Steiner's four Action Areas: 167 for rerouting, 42 for de-risking, 54 for reducing, 24 for realigning, and 34 global documents. These sources were then categorized by region and/or by country, where this was possible, and by the activities relevant to each action. For Action 1.1, for instance, sources were categorized in relation to REDD+, carbon payments, silvopastoralism, tax mediated responses, wetland protection, value chains, sustainable management of forest, mangrove restoration, responsible demand, and palm oil alternatives.

Each source was then evaluated with respect to identifying consistent unit costs for each action. Where possible, costs were converted into comparable units, such as cost per hectare or per capita, and a comparable time frame, one year. Where this was not possible, the source was discarded from the analysis. Thirty-nine sources were ultimately selected for the cost estimation. These unit costs were then applied to the target areas and populations in Steiner (column 3, Table 1) or to proxy targets (column 4, Table 1), depending on the action.

For the actions where we found multiple estimates of the unit costs that were directly comparable (all actions except 4.1, 4.2 and 4.3), we calculated the variance of the estimates and the standard deviation of the combined variables, assuming the variables were uncorrelated and the covariances were uniformly zero. The standard error of the summed estimate was then calculated.

The geographical targeting of the eleven actions in Steiner is generally clear: the major deforestation hotspots around the world (for Action 1.1), or the need to reduce food loss and waste everywhere (Action 3.2), for example. Several actions are targeted to different farmer types and their specific trajectories. The eleven actions will thus have different emphases in different places as a result. Steiner et al. (2020) recognises five general types of farmer: (1) large-scale commercial farmers; (2) conventional small-scale farmers who are less likely to be digitally connected; (3) conventional small-scale farmers who are more likely to be digitally connected; (4) more extensive farmers in areas of greater climate risk (this category includes pastoralists); and (5) lower-endowment small-scale farmers. Despite the considerable advances made recently, digital connectedness still appears to be a major problem in places and may remain so for some years (FAO and ITU, 2022); large populations in Africa, for example, still lack access to basic digital technologies.

The number of farmers of these different types were estimated by region based on several variables including field size, market access, agricultural land use, ease of accessing credit, and prevalence of climate hazards. The regional numbers were reaggregated for this analysis (Table 2).

For Action 1.1, avoid expansion on 250 million ha of tropical forests and 400 million ha of peatlands, costs per ha were estimated in the places where most (80 percent) of the global forest loss by 2030 is expected to take place, along eleven deforestation fronts, many but not all of which are in the tropics (Steiner et al., 2020). These were then rescaled to the targets shown. Peatland extent information was taken from "The global peatland CO_2 picture: peatland status and emissions in all countries of the world (draft)" at https://unfccc.int/sites/default/files/draftpeatlandco2report.pdf. The source of data on the deforestation fronts was https://globil-panda.opendata.arcgis.com/datasets/deforest

Table 1
Eleven actions to transform the food system (Steiner et al., 2020) and the proxies used to estimate their cost.

	Action	Steiner target	Proxy used
Action Area 1: Reroute	***Action 1.1*** Ensure zero agricultural land expansion in high-carbon landscapes	Globally, avoid conversion of 250 Mha of forests and 400 Mha of peatlands	Cost per ha per year for forests and peatlands, scaled to the Steiner target
	Action 1.2 Enable markets and public-sector actions to incentivise climate-resilient, low emission practices	Bring 200 million farmers into appropriate markets by 2030 via increased profitability and market development	185 million farmers in Pathways 2 and 4 (Table 2) adopting new practices: improved seeds, fertilizers and soil amendments, and micro-irrigation
	Action 1.3 Support prosperity through mobility and rural reinvigoration	Build attractive rural livelihoods, including exits from agriculture, and create 20 million rural jobs by 2030 by investing in infrastructure and youth	Cost of infrastructural development, and cost of safety net policies for facilitating movement out of farming, upscaled to 400 million rural dwellers in low- and lower-middle-income countries
Action Area 2: De-Risk	***Action 2.1*** Secure resilient livelihoods through early warning systems & adaptive safety nets	End dependence on humanitarian assistance for 40 million rural dwellers by 2030, realigning USD 5 billion per year for adaptive safety nets	Cost per person per year of providing social safety nets scaled to 40 million farmers in climate risk hotspots (mostly farmers on Pathway 4, Table 2)
	Action 2.2 Help farmers make better choices	Take climate services to scale by connecting 200 million farmers and agribusinesses to ICT-enabled bundled advisory services by 2030	Cost per person per year of providing digital climate services to 200 million farmers in low- and lower-middle-income countries
Action Area 3: Reduce	***Action 3.1*** Shift to healthy, sustainable, climate-friendly diets	Incentivise substantial reductions in beef and dairy consumption in 15 higher-income countries and all C40 cities by 2030	Cost differential per person per year between current diet and recommended diet applied in the 15 highest-income countries and all the C40 cities, overlaps excluded
	Action 3.2 Reduce food loss and waste	By 2030, target 50% reductions in food loss and waste in five major supply chains where both greenhouse gases and loss or waste are high	Costs per year by supply chain (meat, dairy, roots and tubers, fruits, vegetables, others) allocated to all countries based on their share of the food supply
Action Area 4: Realign	***Action 4.1*** Implement policy and institutional changes that enable transformation	By 2025, realign USD 300 billion of agricultural subsidies to a climate change agenda in 16 countries, improve the "ease of doing business" in 24 sub-Saharan African countries, and significantly improve the readiness score of the ND-GAIN Index in 49 countries	Additional percentage cost of climate-proofing regional investments applied to all the actions in Action Areas 1, 2 and 3
	Action 4.2 Unlock billions in sustainable finance	Unlock USD 320 billion in public and private capital per year to realise business opportunities in the implementation of the SDGs	Costs of de-risking public and private investments allocated to 158 million low-endowment small-scale farmers in Pathway 5 (Table 2)
	Action 4.3 Drive social change for more sustainable decisions	Reach 10 million young people by 2025 through science-based social movements to catalyse climate action in food systems	Costs of educating one student multiplied by the proportion that is climate related, applied to the Steiner target
	Action 4.4 Transform innovation systems to deliver impacts at scale	By 2025, significantly change the approach of public agricultural research for development, with at least 50% of public investment in this research providing end-to-end solutions that support meeting the SDGs related to food	Costs of improving innovation systems and of transforming approaches to gender (including improving female literacy) allocated to all countries in proportion to the number of farmers

Table 2
Indicative number of farms by pathway (millions). Data reaggregated from Table 1 in Steiner et al. (2020).

Region	Pathway					Total
	1: LS	2: CM	3: CL	4: ER	5: LE	
South Asia	2	16	43	9	102	172
Sub-Saharan Africa	3	12	<1	24	31	**70**
Europe & Central Asia	32	3	8	<1	2	**45**
Middle East & North Africa	3	<1	5	1	7	**16**
Latin America & Caribbean	9	5	4	1	3	**22**
Southeast Asia & Pacific	4	33	5	3	14	**57**
East Asia	14	84	105	–	<1	**203**
North America	2	<1	<1	–	–	**2**
TOTAL	**68**	**153**	**170**	**38**	**158**	**587**

Pathways.
1: LS, large-scale commercial.
2: CM, Conventional small-scale, less likely to be digitally connected.
3: CL, Conventional small-scale, more likely to be digitally connected.
4: ER, More extensive farms in riskier environments, including pastoralists.
5: LE, Lower-endowment small-scale farms.
Numbers were calculated based on an incomplete factorial classification using these variables from global data sets:

- Field size (Fritz et al., 2015): very small, <0.5 ha; small, 0.5–2 ha; medium, 2–100 ha; large, >100 ha.
- Market access: travel time to nearest city of >50,000 people (Weiss et al., 2018).
- Agricultural land use (crop, pasture, crop & pasture) from Ramankutty et al. (2008).
- Number of tractors (by country) per 100 square km of arable land (from https://data.worldbank.org/indicator/AG.LND.TRAC.ZS) as a proxy of mechanisation/technology level.
- Ease of accessing credit by country (from https://data.worldbank.org/indicator/).
- Climate hazards from Thornton et al. (2019).
  The estimated human population data for 2020 in each of the five categories were calculated from CIESIN (2018), excluding urban areas. The total number of farms in each of the nine regions were estimated from Lowder et al. (2016) with some updates by Herrero et al. (2017). At the regional level, farm numbers were then allocated across the pathways pro rata according to the rural populations estimated in each pathway.

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Action 1.2 mixes several types of activity to reduce carbon emissions, increase productivity through climate-smart agriculture, improve resilience, and develop markets. A broad spectrum of activities is possible, and here we estimated costs related to a subset of possible climate-smart agriculture (CSA) practices: improved seeds for heat and drought tolerance, fertilizers and soil amendments, and micro-irrigation. Costs were estimated for 185 million small-scale farmers who are less likely to be digitally connected (Pathway 2, Table 2) and farmers operating more extensive production systems in riskier environments (Pathway 4, Table 2) in low- and lower-middle-income countries. To convert the unit cost per ha to the unit cost per farm, the number of farms in the two pathways were multiplied by average farm size from Lowder et al. (2016).

For Action 1.3, support prosperity through mobility and rural reinvigoration, we assessed the cost in two parts. First, we used estimates from recent infrastructure investment analyses to develop a unit cost per person per year. Then we estimated the cost per person of establishing safety net policies to facilitate migration out of failing farming systems. As a proxy, we used recent analysis of the impact of migrant capital on the structure of rural labour markets in Malawi, in terms of the cost of workers shifting out of agriculture and into manufacturing or services. These unit costs were then upscaled to 400 million rural dwellers in low- and lower-middle-income countries. Rural population data were from the Oxford Poverty and Human Development Initiative (Alkire and Kanagaratnam, 2018) for the most recent year reported in the dataset, supplemented where necessary with other data as outlined in Thornton et al. (2022).

For Action 2.1, secure resilient livelihoods and value chains through early warning systems and adaptive safety nets, a unit cost per person per year was estimated from two reviews of safety net programs (Table 3), and the average cost was applied to the farmers in Pathway 4 (Table 2) in the climate risk hotspots identified by Jarvis (2021) in the Middle East-North Africa, sub-Saharan Africa, Latin America and Caribbean, East Asia, Southeast Asia and South Asia, scaled to 40 million farmers in total.

For Action 2.2, taking climate services to scale by connecting 200 million farmers and agribusinesses to ICT-enabled bundled advisory services, the unit costs per farmer per year were averaged from three recent sources (Table 3) and applied to 200 million farmers in low- and lower-middle-income countries. The unit costs include the annual recurring costs and up-front costs including advocacy and extension costs, although not the hard infrastructure costs (Ferdinand et al., 2021).

For Action 3.1, incentivising shifts to healthy and sustainable climate-friendly diets, the unit cost per person per year was calculated as the difference in cost of a recommended diet compared with the current diet, averaged across three sources, for the population of the 15 highest-income countries (from https://data.worldbank.org/indicator/NY.GDP.PCAP.CD) and all the C40 cities (https://www.c40.org/news/10-years-of-results-c40-by-the-numbers/), with any overlaps being excluded. C40 is a network of the world's megacities committed to addressing climate change through collaboration, sharing knowledge and driving meaningful, measurable and sustainable action on climate change. Ten percent of the resultant total cost was assumed to be needed for spending on public health promotions, supporting labelling and certification, promoting awareness campaigns and social movements, and exploring possibilities for consumption taxes and subsidies.

For Action 3.2, reducing food loss and waste, costs were estimated from two sources (Table 3) on reducing post-harvest losses via improving electricity, paved roads and rail and road capacity, and on improving cold and dry storage, rural and wholesale market facilities, and processing facilities. The average costs were then allocated across six major food supply chains and then across countries based on their share of the food supply (kg per person per year). Food supply data were from FAOSTAT food balances for 2019, https://www.fao.org/faostat/en/#home.

Action 4.1 in Steiner et al. (2020), implement policy and institutional changes that enable transformation, includes the realigning of agricultural subsidies. For simplicity and given the difficulty of finding a more direct proxy, we used an "overhead" cost of 16% (ADB, 2018) as the additional cost of climate proofing investments and applied this to the total cost of Actions 1.1 through 3.2. In general, subsidies need to be reduced and repurposed, as argued by many authors because of their damaging environmental impacts (see Laborde et al. (2021), for example). Nonetheless some subsidies are crucial to stimulate production and change (as in Africa), but even here they need to be reformed and eventually phased out (Just Rural Transition, 2022). We have assumed the costs of such subsides are largely captured under this Action.

Action 4.2, unlock billions in sustainable finance: For the public-sector, we used a forecast of incremental climate risk debt to 2030. For the private sector, we estimated the decrease in project costs needed to increase the benefit-cost ratio of a portfolio of regional adaptation projects to at least 3.5. This level of BCR appears realistic for adaptation projects (Harris and Orr 2014; Azumah et al., 2020). The regional totals of public plus private de-risking were then allocated across the 154 million farmers in Pathway 5 (Table 2).

For Action 4.3, driving social change for more sustainable decisions, we estimated the cost of this action using education costs of young people in OECD countries as a proxy, multiplied by the proportion (of education) that is aimed at being climate related.

For Action 4.4, transforming innovation systems to deliver impacts at scale, we averaged costs from several sources (Table 3) on estimated expenditures needed to enhance the efficiency of agricultural research for development. To these we added costs aimed at reducing the gender gap with respect to female literacy and education and access to productive resources. These costs were then allocated to countries

Table 3
Targets, costs and data sources for eleven actions to transform the food system.

	Action	Target in Steiner et al. (2020)	Proxy targets used in the analysis	Unit cost	Sources	Action cost
Action Area 1: Reroute	Action 1.1 Ensure zero agricultural land expansion in high-carbon landscapes	Globally, avoid conversion of 250 Mha of forests and 400 Mha of peatlands	250 Mha forests	Forest: USD 1460 per ha per year	Mean of Crossman et al. (2011), Garcia et al. (2017), Rai et al. (2017)	USD 753 billion
			400 Mha peatlands	Peatland: USD 970.5 per ha per year	Mean of Glenk et al. (2018), Okumah et al. (2019), Hansson and Dargusch (2018)	
	Action 1.2 Enable markets and public-sector actions to incentivise climate-resilient, low emission practices	Bring 200 million farmers into appropriate markets by 2030 via increased profitability and market development	185 million farmers adopting new practices	Improved seeds: USD 147.13 per ha per year	Mean of Cacho et al. (2020), Harris and Orr (2014), Sain et al. (2017)	USD 181 billion
				Fertilizers & soil amendments: USD 379.78 per ha per year	Mean of Harris and Orr (2014), Nowak et al. (2020)	
				Micro-irrigation: USD 273.08 per ha per year	Mean of Siderius et al. (2021), You (2008), Xie et al. (2014)	
	Action 1.3 Support prosperity through mobility and rural reinvigoration	Build attractive rural livelihoods, including exits from agriculture, and create 20 million rural jobs by 2030 by investing in infrastructure and youth	Unit costs upscaled to 400 million rural dwellers in low- and lower-middle-income countries	Infrastructural development: USD 286.88 per person per year	Mean of Asian Development Bank (2017), AfDB (2018), FAO (2020)	USD 116 billion
				Safety net policies for facilitating movement out of farming: USD 3.57 per person per year	Dinkelman et al. (2017)	
Action Area 2: De-Risk	Action 2.1 Secure resilient livelihoods through early warning systems & adaptive safety nets	End dependence on humanitarian assistance for 40 million rural dwellers by 2030, realigning USD 5 billion per year for adaptive safety nets	Unit costs scaled to 40 million farmers in climate risk hotspots	Provision of social safety nets: USD 140.74 per person per year	Mean of FAO & ZEF (2018), World Bank (2018a)	USD 5.6 billion
	Action 2.2 Help farmers make better choices	Take climate services to scale by connecting 200 million farmers and agribusinesses to ICT-enabled bundled advisory services by 2030	Unit costs applied to 200 million farmers in low- and lower-middle-income countries	Digital climate service provision: USD 12.09 per farmer per year	Mean of Ferdinand et al. (2021), Gangopadhyay et al. (2019), FAO & ZEF (2018)	USD 2.4 billion
Action Area 3: Reduce	Action 3.1 Shift to healthy, sustainable, climate-friendly diets	Incentivise substantial reductions in beef and dairy consumption in 15 higher-income countries and all C40 cities by 2030	Unit cost applied to the population of the 15 highest-income countries and all the C40 cities	Cost differential between current diet and recommended diet: USD 380.88 per person per year	Mean of Herforth et al. (2020), Hirvonen et al. (2019), Temple and Steyn (2011)	USD 35 billion
	Action 3.2 Reduce food loss and waste	By 2030, target 50% reductions in food loss and waste in five major supply chains where both greenhouse gases and loss or waste are high	Unit costs allocated across six supply chains and all countries based on their share of the food supply	Total cost per year by supply chain (meat, dairy, roots and tubers, fruits, vegetables, others)	Mean of FAO, IFAD and WFP (2015), Rosegrant et al. (2018)	USD 12.6 billion
Action Area 4: Realign	Action 4.1 Implement policy and institutional changes that enable transformation	By 2025, realign USD 300 billion of agricultural subsidies to a climate change agenda in 16 countries, improve the “ease of doing business” in 24 sub-Saharan African countries, and significantly improve the readiness score of the ND-GAIN Index in 49 countries	Not applicable	Cost of climate-proofing regional investments adds 16%. As a proxy for this action, we used 16% of the costs of Actions 1.1–3.2	Asian Development Bank (2017)	USD 177 billion
	Action 4.2 Unlock billions in sustainable finance	Unlock USD 320 billion in public and private capital per year to realise business opportunities in the implementation of the SDGs	Unit costs by region allocated to 154 million low-endowment small-scale farmers	Cost of de-risking public investment: USD 15.6 billion per year	Buhr et al. (2018)	USD 20 billion
				Cost of de-risking private investment per person per year: USD 2.95 (Asia); USD 2.31 (sub-Saharan Africa); USD 2.22 (Middle East-N Africa); USD 9.12 (Latin America and Caribbean)	Ferrarese et al. (2016)	
	Action 4.3 Drive social change for more sustainable decisions	Reach 10 million young people by 2025 through science-based social movements to catalyse climate action in food systems	Unit costs applied to 10 million young people	Education cost per student that is climate related: USD 2000 per student	OECD (2020a), OECD (no date)	USD 20 billion
	Action 4.4 Transform innovation systems to deliver impacts at scale	By 2025, significantly change the approach of public agricultural research for development, with at least 50% of public investment in this research providing end-to-end solutions that support meeting the SDGs related to food	Unit costs allocated to all countries proportionally to the number of farmers	Cost of improving innovation: USD 10.1 billion per year	Mean of Beintema et al. (2020), CoSAI (2021), FAO, IFAD and WFP (2015), FAO (2020)	USD 15 billion
				Cost of transforming approaches to gender, including improving female literacy: USD 5.2 billion per year	FAO (2020), Food and Land Use Commission (2019), World Bank (2018b)	

proportionally to the number of farmers in all the five pathways (Table 2).

3. Regional costs of reconfiguration

We estimate that USD 1.3 ± 0.1 trillion per year are needed to 2030, the time horizon of Steiner et al. (2020), to implement the eleven actions and achieve systemic food system reconfiguration (Table 4). Action 1.1, avoided conversion of 250 Mha of forests and 400 Mha of peatlands, requires 56 percent of the total. These costs are spread across all areas of the globe, as there are key areas of forest and peatland in both tropical and temperate zones. Action 1.2, enabling markets and public-sector actions to incentivise climate-resilient, low-emission practices, has the next largest cost (USD 181 billion), 15% of the total. Rerouting farming and rural livelihoods to new trajectories is the Action area (#1) with the greatest cost.

The costs are large for Action 4.1, implementing policy and institutional changes that enable reconfiguration (USD 177 billion) and for Action 1.3, supporting prosperity through mobility and rural reinvigoration (USD 116 billion). Smaller costs in the range USD 15–35 billion apply to each of Action 3.1, shifting to healthy, sustainable, climate-friendly diets; Action 4.2, unlocking billions in sustainable finance; Action 4.3, driving social change for more sustainable decisions; and Action 4.4, transforming innovation systems to deliver impacts at scale. The remaining actions have costs that are smaller still: USD 2–12 billion each. As Steiner et al. (2020) argue, action on all elements simultaneously is required, the actions undertaken together offer better prospects for moving food systems onto sustainable and more equitable trajectories than a piecemeal approach.

There are wide regional variations in these costs of food system reconfiguration (Table 4 and Fig. 1). Large amounts are needed particularly for sub-Saharan Africa, SE Asia and the Pacific, and Latin America and the Caribbean. The great majority (more than 70 percent) of the costs in N America, Europe and Central Asia, and Latin America and the Caribbean are for avoiding conversion of high-carbon forest and peatland landscapes to agriculture.

To put the total cost into context, it is equivalent to about 15 percent of the estimated USD 9 trillion yearly monetary value of global food consumption (van Nieuwkoop, 2019) and about 1.5 percent of global GDP. It amounts to 15 percent of what was mobilised globally by governments within four months of the start of the Covid-19 pandemic (Herrero and Thornton, 2020) and to less than 7 percent of the hidden negative externalities generated by the current food system each year (Hendriks et al., 2021). Furthermore, food system reconfiguration promises major benefits, and not just through increased food system

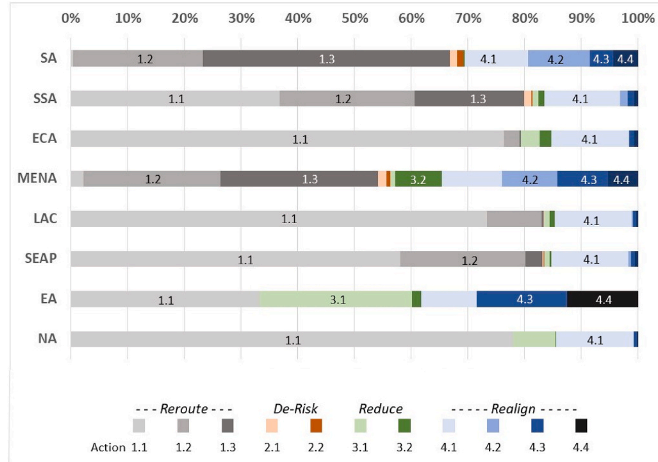

Fig. 1. Estimated relative cost by region by action. Actions are listed in Table 1.

resilience. Likely improvements in global human health have been valued at more than USD 1 trillion per year (FOLU, 2019). Substantial reductions in the annual USD 7 trillion of environmental cost of current food systems could be achieved, not only in reducing the carbon and biodiversity losses arising from land conversion but also reducing air pollution and blue (fresh) water use (Hendriks et al., 2021). Major savings could also be achieved by reducing food loss and waste, estimated to cost USD 2.6 trillion per year (FAO 2021). The eleven actions outlined above could contribute a substantial portion of these benefits, though achieving all of them would require considerable investment in other sectors too.

Technological and social innovation, and the processes and institutions they modify, show strong synergies and antagonisms (Herrero et al., 2021). This is true both within and between sectors, in the latter case with innovation in other sectors spilling over into the agricultural sector and often being repurposed in the process. How these interactions may play out in the future cannot be known with any certainty. Nevertheless, it seems highly likely that synergistic and overlapping effects between some of the eleven actions will lead to a decline in the annual costs presented here. Many historical precedents suggest that synergies from innovation in the energy, health and ICT sectors, to name just three, will likely spill over to the food sector, further reducing the cost of food-system reconfiguration through time.

We acknowledge several limitations of this work. First, a major underlying assumption is that changes in behaviour can be brought about

Table 4
Estimated action costs by region, USD billion per year. Actions are listed in Table 1.

Region	Reroute			De-Risk		Reduce		Realign				Total, Actions 1.2–4.4	Total, All Actions
	Action 1.1	Action 1.2	Action 1.3	Action 2.1	Action 2.2	Action 3.1	Action 3.2	Action 4.1	Action 4.2	Action 4.3	Action 4.4		
South Asia	0.4	27.5	52.5	1.5	1.4	–	0.2	13.4	13.2	4.9	5.3	119.9	120.3
Sub-Saharan Africa	96.4	62.2	50.4	3.4	0.5	2.7	2.8	35.0	3.4	3.0	1.9	165.3	261.7
Europe & Central Asia	177.0	6.4	0.6	–	<0.1	7.8	4.8	31.5	–	2.3	1.5	55.0	232.0
Middle East-North Africa	0.3	3.2	3.7	0.2	0.1	0.1	1.1	1.4	1.3	1.2	0.7	13.0	13.3
Latin America & Caribbean	185.6	24.4	0.9	0.1	<0.1	2.3	2.3	34.5	0.4	1.7	0.7	67.5	253.1
Southeast Asia & Pacific	151.6	57.5	8.0	0.4	0.3	2.5	0.8	35.4	1.3	1.8	1.5	109.5	261.1
East Asia	8.5	–	–	–	–	6.9	0.4	2.5	–	4.1	3.2	17.1	25.6
North America	133.4	–	–	–	–	12.7	0.2	23.4	–	1.0	0.4	37.7	171.1
Total by action	**753.1**	**181.2**	**116.2**	**5.6**	**2.4**	**35.0**	**12.6**	**177.0**	**19.7**	**20.0**	**15.3**		**1338.1**
Total by action areas	**1050.4**			**8.0**		**47.6**		**231.9**				**584.9**	**1338.1**

via inducements through policy change, well-targeted financial flows, and education to help drive social change, rather than via the imposition of penalties and restrictions. Whether carrots alone would suffice to induce behavioural changes of the type and scale needed, is a key uncertainty. Second, despite the many sources of information consulted for cost estimation, we found surprisingly few studies with adequately detailed costs data that were directly comparable with each other. Third, the cost of some of the actions could not be estimated directly, and for these we had to use proxy variables. All four actions in Action Area 4 are of this kind: costs of implementing policies and institutional changes, or of driving social change, for example, are challenging to quantify, even indirectly. Fourth, there are likely to be both synergies and some trade-offs in implementing the eleven actions. We attempted to minimise these by targeting specific actions to specific food system players. Some overlaps remain. For example, costs were estimated for farmers in pathway 4 in lower-income countries in relation to Action 1.2 (CSA implementation), Action 2.1 (early-warning systems) and Action 2.2 (digital climate advisories). The individual costs of these three actions implemented by the same farmer are likely not strictly additive; this might apply, for example, to shared advocacy and extension costs, and possibly to some of the shared infrastructure costs associated with Action 1.3 as well. There may also be some trade-offs: for example, getting CSA implementation going on 185 M farms in lower- and middle-income countries may increase national greenhouse gas emissions from the agricultural sector at least over the short term, in the situations where crop productivity increases partly owing to better soil nutrition and some use of inorganic fertilizers.

4. Concluding comments

Despite the limitations of the study, an estimate of the costs that may be needed to reconfigure food systems could have considerable value in helping to catalyse action at global and national levels. Adaptation cost estimates have grown through time, in part because the full impacts of climate change on food systems are becoming increasingly understood. In 2009, adaptation costs of USD 49–171 billion per year were estimated for agriculture, water, human health, coastal zones and infrastructure (Parry et al., 2009). Recent estimates of adaptation investments for infrastructure are in the range 2–8 percent of GDP, or several trillion dollars each year (Rozenberg and Fay, 2019). Estimates of the cost of reconfiguration at a national level, linked to a specific set of concrete actions, could be a useful input into investment planning to help guide implementation of national adaptation and mitigation actions to meet targets under the Paris Agreement. At the same time, effective climate action in all sectors, particularly mitigation, would help offset some of the food system reconfiguration costs identified here.

Official development assistance in 2019 was USD 168 billion (OECD, 2020b), suggesting a massive financing gap for food system reconfiguration. Several options could potentially contribute to filling the gap - increases in official development assistance, increased climate finance from the public and private sectors, levies and taxes, redirecting existing funding streams (Rozenberg and Fay, 2019; Robinson et al., 2021; Gautam et al., 2022) – but all are politically charged. Ultimately, what is lacking is the collective political will and follow-through to put in place the incentives for change, and the financial and policy enablers that will foster such change, to move towards the sustainable and equitable food systems that we urgently need.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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