A future food system for healthy human beings and a healthy planet

A STAP document

June 2018

STAP SCIENTIFIC AND TECHNICAL ADVISORY PANEL

An independent group of scientists that advises the Global Environment Facility

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ABOUT STAP
The Scientific and Technical Advisory Panel (STAP) comprises seven expert advisors supported by a Secretariat, who are together responsible for connecting the Global Environment Facility to the most up to date, authoritative and globally representative science. http://www.stapgef.org

ABOUT GEF
The Global Environment Facility was established on the eve of the 1992 Rio Earth Summit to help tackle our planet's most pressing environmental problems. Since then, the GEF has provided over $17.9 billion in grants and mobilized an additional $93.2 billion in co-financing for more than 4500 projects in 170 countries. The GEF has become an international partnership of 183 countries, international institutions, civil society organizations, and the private sector to address global environmental issues. http://www.thegef.org

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CONTENTS

SUMMARY

Food production will need to increase by more than 50% to feed a global population of more than 9 billion people by 2050, and to meet the increased demand for protein, driven by rising incomes. The challenge is to achieve this in a sustainable way without compromising the natural capital and ecosystem services which support food production.

The current food production and consumption model is a "take-make-waste" linear system with significant deleterious effects on the environment. The agri-food sector, from the farm to the plate, contributes nearly one-quarter of total global greenhouse gas (GHG) emissions. A further 10 to 15% of total GHGs come from converting forests and peatlands to farmland. The sector also causes around two-thirds of biodiversity loss and extensive land and water degradation. Over 70% of freshwater withdrawals are used for agriculture, mostly for irrigation. The science confirms that significant changes to the present food supply system are urgently required.

Many scientific studies offer potential solutions to improving sustainability in the agri-food sector in both the short and long-terms. Making the transition to a more sustainable food supply system would be assisted by reducing food losses and wastes and implementing a "circular economy" approach. This aims to recycle nutrients and water, adopt conservation farming systems, improve resource use efficiency, displace fossil fuels with renewable energy, and maintain materials and resources in the economy at their highest utility and value for as long as possible. As a result, food production systems would become more resilient to climate change impacts, and other global goals of the GEF would be advanced, such as clean water, sustainable forest management, climate change mitigation, biodiversity conservation and avoiding land degradation.

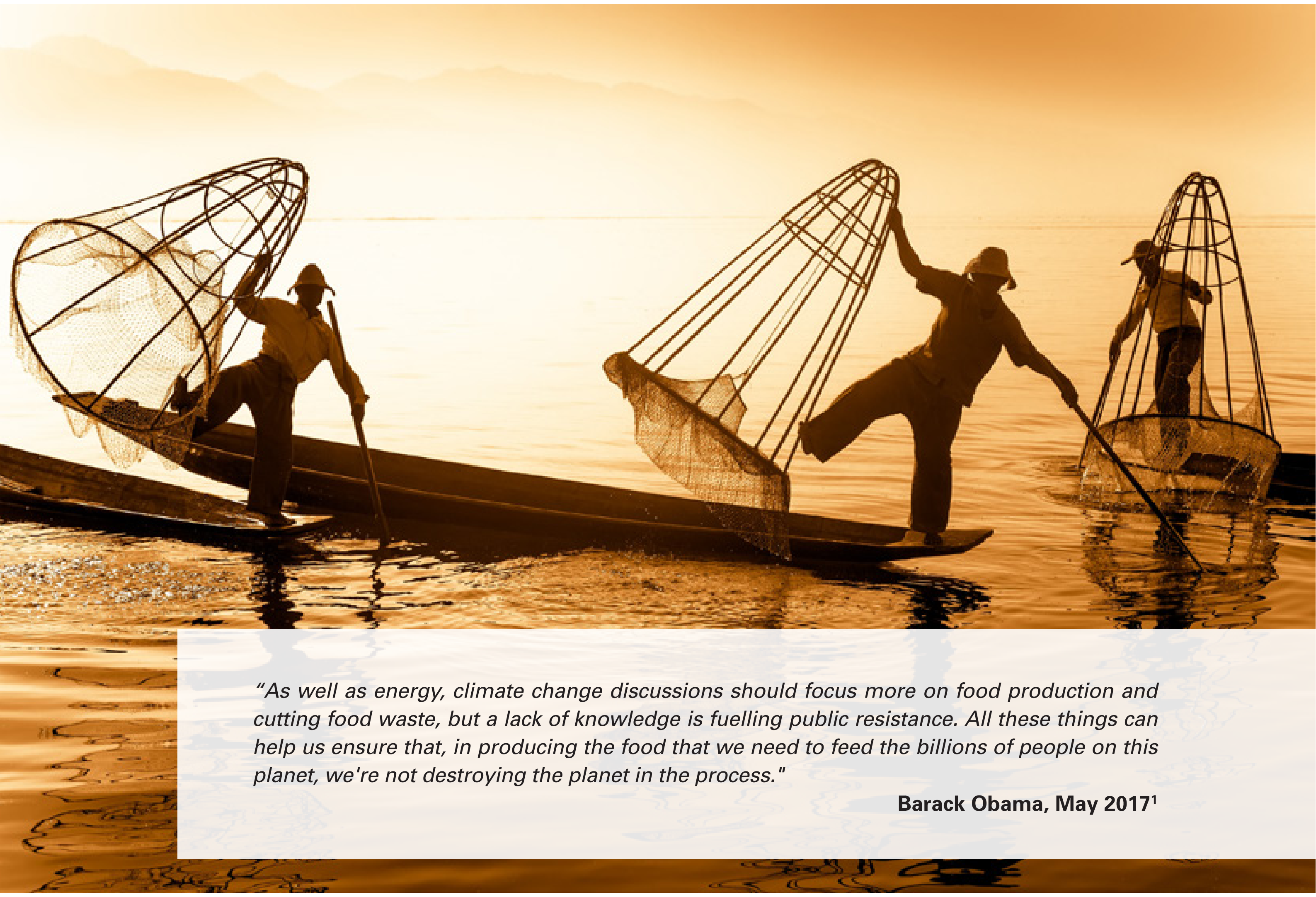
In the short term, in addition to reducing food losses and wastes, improved sustainability of the food supply system could be achieved by the more efficient use of resources. Reducing inputs per unit of food production whilst increasing productivity would help avoid negative impacts on biodiversity, soil quality, freshwater supplies, and the atmosphere. Practical examples include conservation tillage; efficient food processing operations and transport logistics; sustainable land management practices; precision farming to apply fertiliser, water, and chemical inputs judiciously; improved post-harvest storage; reducing consumption of animal protein; and better access to markets to reduce food losses. STAP recommends that the GEF encourage one or more of these strategies be incorporated in food-related projects in GEF-7. This experience will provide useful information to inform complex projects attempting to achieve a full circular economy.

In the longer-term, more ambitious action will be required to improve sustainability and avoid further degradation of land, water and nutritional quality of food. Adopting the circular economy approach for the agri-food sector will involve the development of agro-ecological systems and instigating innovative energy-smart and climate-smart production systems to reduce competition for productive land and freshwater and avoid further loss of soil fertility.

The GEF is already attempting to reconcile increased food production with fostering long-term sustainability and resilience through the Food Security and the Commodities Integrated Approach Pilots (IAPs). These integrate management of land, water, soil, and genetic resources with maintaining ecosystem services and should yield important 'lessons learned' to build upon.

The planned GEF Impact Program (IP) on Food Systems, Land Use, and Restoration will focus on promoting sustainable food systems to tackle negative externalities; deforestation-free agricultural commodity supply chains; and large-scale restoration of degraded landscapes for sustainable production and ecosystem services. This IP will provide an opportunity for researchers, businesses, and practitioners to better understand the complexities and principles involved when working towards a circular economy for agri-food. STAP recommends that child projects under this IP should include involvement of both key stakeholders and circular economy specialists at an early stage of project preparation. Together they would help assess the practicalities of achieving key outputs and outcomes for the project and help develop the project proposal accordingly.

Overall, the GEF is well positioned to support the essential transition needed to feed everyone on the planet adequately whilst avoiding negative externalities and sustaining biodiversity as well as the health of human beings, ecosystems, and the planet.



"As well as energy, climate change discussions should focus more on food production and cutting food waste, but a lack of knowledge is fuelling public resistance. All these things can help us ensure that, in producing the food that we need to feed the billions of people on this planet, we're not destroying the planet in the process."

Barack Obama, May 2017[1]

1. WHAT IS THE ISSUE?

Global food production continues to grow to meet the demand from rising populations and incomes. Food insecurity today is mainly due to conflicts, droughts, and floods rather than from systemic production shortfalls[2]. Today's food supply system[3] produces around 2.8 billion tonnes of cereals and 330 million tonnes of meat annually[4], largely thanks to the "Green Revolution" of the mid-20th Century that involved new crop varieties, fertilisers, agri-chemicals, mechanisation and improved farm management. Land use change from forests and peatlands to provide more agricultural land has also contributed to growth in the food supply.

However, food production needs to increase by a further 50% by 2050 to meet the projected demand[5]. This needs to be achieved sustainably in order to produce nutritious food without compromising natural capital and ecosystem services that support food production. This target could possibly be achieved by changing consumption patterns[6]; increasing the productivity of crops and animals (e.g. tonnes per hectare, milk solids per cow); adopting the circular economy approach; reducing food losses; and minimising negative externalities in the food supply value-chain. Innovative technologies can also contribute to this goal.

From subsistence farming to medium and large, vertically-integrated corporations, a range of adverse environmental impacts are frequently observed. The modern industrial food supply system consumes resources and energy inputs on-farm and in pre-processing, storage, transport, food processing, retailing and cooking. A significant proportion of these resources are wasted due to the failure to consume around one-third of the food produced as a result of losses in storage and wastes at the retail and consumption stages.

The agri-food sector consumes over 30% of total global end-use energy, mostly from fossil fuels, and emits around 22% of total global anthropogenic greenhouse gases (GHG)[7, 8], including methane (from livestock and paddy rice) and nitrous oxide (from fertiliser and animal urine). Land use change from converting forests and peatlands to agricultural use contributes a further 10 to 15% of total emissions.

The sector also causes almost two-thirds of biodiversity loss, causes extensive land and water degradation[9], depletes fishing stocks, and over-exploits the world's aquifers. The sector needs to be transformed so it can produce enough nutritious food for everyone while minimising its negative impacts on the planet's resource base, climate, and ecosystems[10].

The modern food supply system is mainly linear with respect to inputs of nutrients, energy, water and increasing distance to markets (Fig. 1a). Transition to a more circular economy (Fig. 1b) would improve resource use efficiency, substitute renewable or recyclable resources for finite ones, and enhance ecosystem services from pasture, crop, and forest lands[11]. In addition, agro-ecosystems could be designed to provide environmental health, watershed functions, disaster risk mitigation and healthy human habitats; biodiversity could be sustained and landscapes in production regions re-wilded; food losses and wastes could be minimised and consumption patterns changed; and sound human nutrition levels could be provided universally[12].

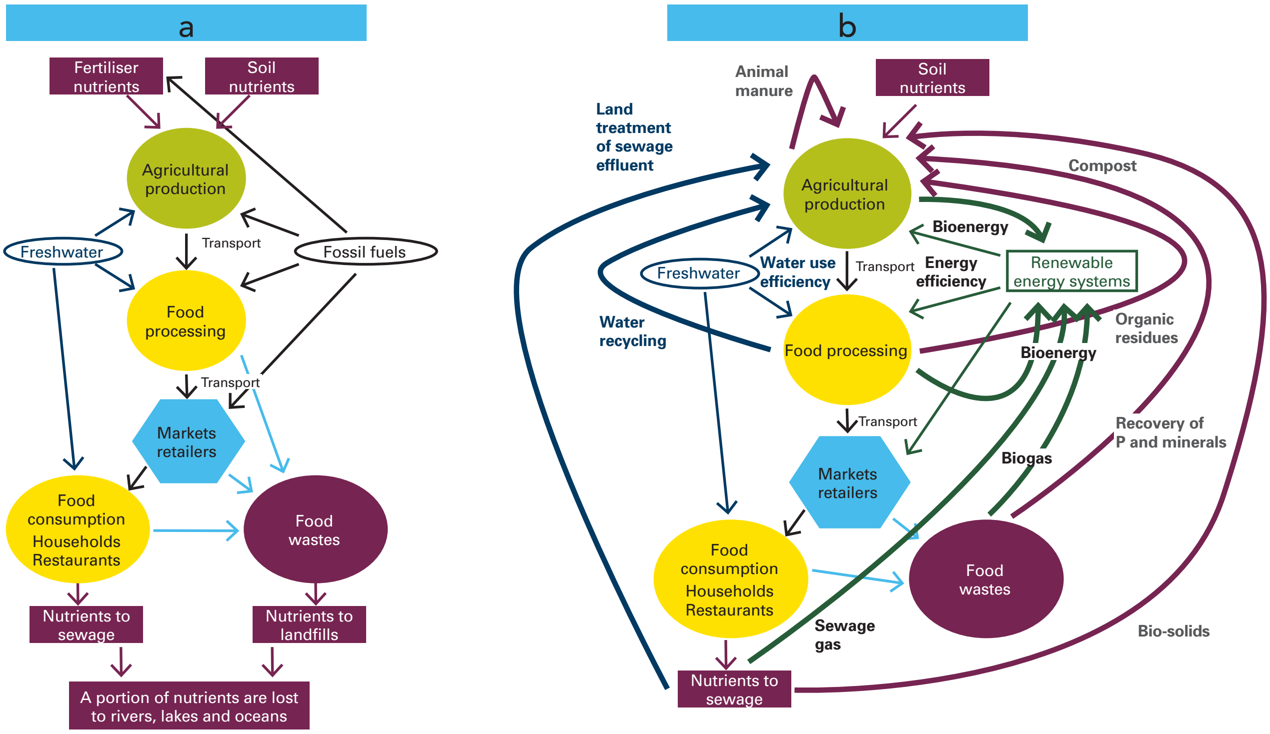


Figure 1. a) The conventional food supply system is mainly linear, relying on the extraction of non-renewable resources and the subsequent loss and waste of nutrients causing pollution[13]. A few circular elements are already common practices, such as applying animal manure to land, but these are limited.

b) A circular food economy uses renewable energy systems linked with improved energy efficiency, can recover and recycle nutrients to farmland (red); reduce food losses and re-use wastes for animal feed, compost and bioenergy (green); and recycle water and increase use efficiency (blue) to reduce demand for freshwater and avoid pollution of waterways.

2. WHAT DOES THE SCIENCE SAY?

The present world food system is not sustainable in the long term due to many factors. Present scientific analysis confirms that significant changes are urgently required, and many scientific studies offer potential solutions to improve sustainability in both the short and long terms. For example, implementing the individual components that contribute to a circular economy approach (Fig. 1b) would aid the transition to a more sustainable food supply system.

A range of potential technical and behavioural solutions, as identified in the scientific and practitioner literature, are summarised in strategic terms below. Food systems exacerbate climate change and are not resilient to it. This is covered by the first three strategies listed. Protecting sustainable land and water use are critical for food production and are covered by the next three. For these six general categories, as well as for improving resource use efficiency, some recommendations are made by STAP in Section 4. These advise the GEF on how its programs and investments can help make the global food supply system become more sustainable in the near and longer term future.

• **Reducing GHG emissions in the value-chain**

Keeping the global temperature rise below 1.5°C above pre-industrial levels would mean achieving net zero emissions across all sectors of the global economy well before the end of this century. However, the current agricultural development pathway projections show sector emissions would not be cut sufficiently[14]. So either other sectors will need to achieve negative emissions (at an acceptable marginal cost per tonne of CO_2-equivalent avoided) to offset future agri-food sector emissions or, more likely, the agri-food sector will need to transform from its present state. Options to reduce methane emissions from rice paddy fields and ruminant livestock, and to reduce nitrous oxide from animal urine and the application of nitrogenous fertilisers, appear limited[15]. Transformative technical and policy options and investments are therefore urgently needed.

Increasing productivity at the global scale[16], avoiding food losses, and giving special attention to the role of carbon stocks in soils and biomass have good potential to reduce emissions intensity in the short term. Improving the efficiency and productivity of agricultural production could potentially reduce emissions by up to 1.1 billion tonnes of CO_2-equivalent by 2030[17]. This would be consistent with global emission pathways that limit warming to below 2°C. In addition, sequestering carbon is possible in many soils by incorporating organic matter and/or adding biochar[18], as well as through re-vegetation and agricultural land-use mosaics[19].

• **Transition to a renewable and efficient energy supply**

A vast amount of energy is needed to bring the world's food to the table[20]. This includes energy for on-farm production and harvesting, fertiliser manufacture, food processing, transport, storage, and cooking. Except for the traditional use of biomass to provide heat (mainly from combustion of fuelwood and dung) most of this energy comes from fossil fuels. Future price shocks in the energy market would, therefore, affect the price of food for all.

The environmental and economic impacts of the global food system can be reduced by the rapid and wide deployment of renewable energy systems, as well as greater energy efficiency throughout the value-chain.

• **Climate-proofing future food production**

Agricultural production systems are highly vulnerable to the impacts of climate change. In warm regions, higher temperatures will stress crops and livestock, thereby reducing productivity and product quality. Elsewhere, increased incidence of droughts, floods, and spread of pests and diseases will cause further losses. Conversely, in temperate to high latitudes, climate change could possibly increase crop yields, thus widening existing disparities[21]. However, 'protected agriculture', urban agriculture, hydroponics, biocultures, algae, and aquaculture all offer more climate-resilient means of food production.

Stakeholders throughout the agri-food sector will need to become more resilient[22] in the face of a changing climate. New and innovative climate-proof food production systems, such as drought-resistant crop species, conservation tillage methods to reduce soil erosion under high rainfall events, and protected vertical horticulture systems, will need to be further developed and widely deployed.

• **Higher productivity to reduce land clearing**

Measures to increase productivity that are well understood (for example, system of crop intensification – Box 1) can help address food security as well as reduce GHG emissions. Novel mitigation options to address non-CO2 emissions, such as methane inhibitors for ruminant livestock, are being developed. To be successfully taken up by farmers, they need to increase, or at least maintain animal productivity[23]. Such technologies may achieve a reduction in GHG emissions intensity per unit of food produced but, if not well-designed, could result in an increase in absolute GHG emissions.

Expansion of grains, soybeans, palm oil, sugar, beef and other commodities has caused worldwide losses of carbon stocks, forests, grasslands, and biodiversity[24]. Agricultural practices and inputs can seriously interfere with wildlife habitat; agri-chemicals can affect non-pest species (such as bees, birds, and fish), disrupt reproduction, and contaminate water and food sources; tillage can destroy soil structure, microbiota, and birds' nests; and water diversion can disrupt natural water supplies. At the same time, large areas of land are being farmed at levels well below their potential optimal productivity[25].

Improving the productivity per hectare on existing land will reduce the need for further land clearing and hence also reduce biodiversity loss.

BOX 1.
System of crop intensification (SCI)

Originally introduced for rice crops[26, 27] SCI is claimed to give higher productivity, use less water and land, reduce production costs and generate higher income for farmers. It is part of a family of agro-ecological methods and strategies aiming to give good economic returns, especially for smallholders with limited resources, together with environmental benefits. These methods include conservation agriculture, pest management, nutrient management, agroforestry, holistic rangeland management, aquaculture, and water harvesting all integrated into the farming system. The methods determined for rice crop intensification have also been extrapolated to wheat, sugarcane, potatoes and other crops[28, 29].

- **Conservation farming to avoid land degradation**

Around one-third of the agricultural land is "moderately to highly degraded due to erosion, salinisation, compaction, acidification, and chemical pollution"[30]. Severe cases result in 2 to 5 million hectares of cropland being abandoned each year[31]. This is the result of unsustainable farming practices such as cultivation of slopes, over-grazing, inefficient irrigation resulting in soil salinisation, and excessive use of nitrogenous fertilisers leading to soil acidification[32]. Soil organic matter has declined in many croplands through stubble burning or removal of crop residues for animal feed, bedding or bioenergy use and ecosystems have also been affected.

Conservation farming systems, including organic farming, the addition of biochar to the soil, and improved farm management systems, can help slow the current rate of land degradation in some regions.

- **Better water management to improve water quality and watershed functions**

Over 70% of the world's total freshwater withdrawals are for agriculture[33] with irrigated land producing about 45% of the world's food. Extraction of surface water affects lake, stream and river ecology and flow rates[34]. Major aquifers have been depleted and water tables lowered where extraction has been greater than the recharge rate, particularly in the USA, China, and South Asia. In addition, glacial retreat is threatening future freshwater supplies, for example, in East Africa and the Andean countries of Latin America. Local waterways, aquifers, and estuaries are often adversely affected by agricultural pollution and sediment, with increasing impacts on wildlife biodiversity. Freshwater sources have also been extensively polluted by agri-chemicals, fertiliser run-off, livestock wastes, food processing effluents, and nitrate infiltration.

Contaminated watersheds can be restored to acceptable ecological quantity and quality by improving local farm management and food processing systems, monitoring water availability and managing extraction rates.

- **Improving resource use efficiency**

Over the past 50 years, crop production has tripled due to increased land clearing, a doubling of the total area irrigated, a five-fold increase in fertiliser application, and a 30-fold increase in the use of agri-chemicals[35]. Continuing along this pathway is not sustainable.

More efficient use of resources can improve the sustainability of food supply systems by reducing inputs per unit of food production whilst increasing productivity and avoiding negative impacts on biodiversity and water quality[36].

Examples of how the GEF might incentivise improving resource efficiency in both the short and long terms are discussed in Section 4.

3. WHY IS THIS IMPORTANT TO THE GEF?

The challenge is to feed over 9 billion people by 2050 whilst significantly reducing the negative externalities. Food production will need to increase by more than 50% by 2050 and also meet the increasing demand for protein as rising incomes expand the middle classes, especially in Asia.

Currently, the sector causes almost two-thirds of biodiversity loss, extensive land and water degradation[37], depleted fish stocks, and over-exploitation of the world's aquifers. Therefore the sector needs to be transformed so it can produce enough nutritious food for everyone while minimising its negative impacts on the Planet's resource base, climate, and ecosystems[38]. Supporting sustainable intensification to reduce environmental degradation and negative externalities from food supply systems and value-chains[39] can be achieved by promoting well-understood best practices and innovative tools. To provide a secure supply of quality food for all without increasing the environmental impacts, many of the possible solutions will need integrated systems thinking.

Meeting the growing food demand[40] while reducing the negative impacts would be made easier if the wastage of around one-third of the food produced globally was reduced. This stems from both post-harvest handling and storage losses mainly in developing countries, and food wastage by the food-processing industries and consumers mainly in developed countries. In addition, better nutrition can curb the unhealthy diets responsible for the current pandemic in non-communicable diseases which claim 70% of human lives[41].

The global goals of the GEF around land degradation, clean water, sustainable forest management, climate change mitigation and adaptation, and biodiversity conservation cannot be met unless the agri-food sector is better aligned with these objectives.

The GEF is already addressing this through two of the IAPs.

- The Food Security IAP program focuses on fostering long-term sustainability and resilience through integrated management of natural capital (land, water, soil and genetic resources) in Africa. Efforts focus on shifting agricultural productivity to a low-emission and resilient pathway. This entails adopting techniques and approaches that sequester carbon in soils while improving soil quality; improving the accuracy of fertiliser application to minimise agro-chemical residues in water; and carefully managing the production system so that interactions between land, water and energy are considered in land management decisions.

Because the agri-food sector encompasses many disciplines, it has wide-ranging impacts on several of the Sustainable Development Goals (SDGs). The Food Security IAP responds directly to SDG 2 (zero hunger) and SDG 15 (life on land). The child projects under this program also have strong links to SDG 1 (no poverty), SDG 6 (clean water and sanitation), SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production) and SDG 13 (climate action).

- The Commodities IAP program takes an integrated approach to tackling the underlying root causes of deforestation that results from agriculture commodities through value-chain management. Beef, palm oil, and soy production together account for nearly 70% of deforestation globally. The pathways of agricultural production, consumption, and potentially food waste are followed for each of these commodities. Through this approach, the program avoids the risk of improving some activities in the value-chain but then shifting the problem to other activities in the value-chain. Embedding sustainability measures (such as those described in this paper), throughout the food pathways is critical.

In addition, the Impact Program on Food Systems, Land Use, and Restoration planned for GEF-7 will focus on three interrelated priorities:

- promoting sustainable food systems to tackle negative externalities in entire value-chains;
- promoting deforestation-free agricultural commodity supply chains; and
- promoting large-scale restoration of degraded landscapes for sustainable production and ecosystem services.

4. HOW CAN THE GEF RESPOND?

In order to deliver the objectives of the relevant multilateral environmental agreements, the GEF should assess how best to support projects that will change present food consumption patterns and lead to more secure and sustainable food supply systems. This is challenging because major environmental impacts are associated with the conventional agri-food sector, innovative technological developments are evolving rapidly with several close to commercial viability, and a wide range of institutional models directly link agri-business development opportunities with environmental management at both the value-chain and large landscape scales.

Rather than supporting projects which achieve only incremental improvement to conventional, mainly linear, food systems, the GEF should invest in projects that:

- integrate a long-term vision and theory of change for improving productivity;
- promote the circular economy (Fig. 1b) and zero waste concepts;
- value co-products that arise from sustainable production and consumption systems;
- support innovative protein production systems; and
- engage consumers in designing future sustainable food supply systems.

Models of more resource-efficient and less environmentally-damaging systems are available. In addition to using well-understood practices to increase productivity and efficiency, the GEF can play a role by promoting various initiatives that are just starting to reform the global food system in order to "feed a growing global population with healthy food from a healthy planet"[42]. These would have positive net benefits on watershed functions, on the generation of ecosystem services from agricultural landscapes for biodiversity and natural habitats, and on climate change mitigation and adaptation. Overall, this will create a more synergistic relationship between economic, ecological and social systems (including human health and well-being).

Integrating such initiatives synergistically into larger-scale strategies and incorporating them into more ambitious transformation efforts to reduce GHG emissions and restore planetary health would generate integrated models that could guide investment in sustainable food supply systems by governments, civil society, and the private sector.

The GEF should consider incorporating the following elements into its integrated initiatives relating to food supply and consumption:

a. Short term actions

Sustainability of the food supply system can be improved in the short term through supporting more efficient use of resources leading to reduced inputs per unit of food production whilst increasing productivity and avoiding negative impacts on biodiversity and water quality. Many of these are well understood and already supported in past GEF projects and programs

In its current programmes and forthcoming projects relevant to food supply systems, where appropriate, the GEF should continue to support the following initiatives:

- careful management of on-farm production systems, crop residues, stubble and grazing lands to minimise soil erosion and enhance soil fertility[43];
- sustainable land management practices and conservation tillage techniques;
- urban agriculture, bio-cultures and other climate-proof systems, especially those that enable nutrient and water recycling and conservation;
- if technologies and practices used by the leading 10% of practitioners to reduce their emission intensities were adopted by all, this could reduce GHG emissions in the food process by 30%[44];
- improving the efficiency of water and energy use along the food supply chain;
- increasing the installation of renewable energy heat and electricity generation systems to displace fossil fuels and provide greater energy access;
- precision farming, including more accurate fertiliser, irrigation, and agri-chemical applications;
- judicious use of chemical inputs to minimise food, water, and wildlife contamination[45];
- remote sensing, use of drones for pest monitoring, and smartphones for disease diagnosis;
- more efficient food processing operations and transport logistics;
- improved post-harvest storage and better access to markets to reduce food losses; and


Source: Adobe Stock

- creating better consumer education and awareness of food retailing, preparation, cooking and nutrition to help minimise consumer food wastes. Any remaining food wastes can also be converted into feed for animals or for insects that can then be processed to supply protein for consumption by humans, fish or poultry[46].

Exactly "how" the GEF can support these and other specific strategies in the short term will depend on the proponents of food-related projects being aware of the complex issues that involve making the food supply system more sustainable. Providing an understanding of the enormity of the problem and the need to make progress in starting to resolve it should encourage project proponents to consider incorporating at least some of the initiatives listed above into their projects wherever appropriate to do so.

Making the transition of the current linear food supply sector to more of a circular economy concept (Section 1) will require gaining more knowledge and experience of each of the components. This could be achieved by initially undertaking demonstrations of one or more of the technical and behavioural components involved in a circular economy as part of relatively small projects rather than aiming for full integration from the onset. Thus, GEF-7 multi-focal area projects could include, for example, composting of food wastes, recycling of food processing effluents, or conversion of crop by-products to bioenergy. This would help provide a greater understanding of the challenges of achieving a true circular economy from real-world experiences, leading to developing a fully integrated sustainable food supply system in the longer-term.

STAP recommends that proponents of any GEF-7 projects relating to the agri-food sector be encouraged to include one or more additional components linked to the circular economy wherever practical to do so.

b. Longer term actions

In the longer term, additional concerns will need to be addressed if sustainability of the food supply system is to be improved, sectoral GHG emissions reduced, and further degradation of land, water and nutritional quality of food avoided. The GEF could encourage the integration of a number of innovative solutions, as outlined below, into its current and future programs.

This begs the question: "How can the GEF encourage the integration of land, water, energy and climate strategies into agri-food related projects that would lead to incorporating systems thinking around the circular economy?"

Given the magnitude of making the transition from the current linear global food system towards a more complex circular one (Fig. 1), and knowing that the 1.5°C target, or even the 2°C target, of the Paris Climate Agreement, cannot be met without significant GHG emission reductions coming from the agri-food sector (since it is responsible for around 22% of total GHG emissions[47]), the answer will require careful deliberation.

The planned Impact Program (IP) on Food Systems, Land Use, and Restoration currently under development offers an opportunity. Researchers, businesses, and practitioners working towards a circular economy for agri-food are presently having to move up a steep learning curve in order to better understand the complexities involved. Therefore STAP recommends that when a child project under this IP involves one or more of the eleven strategies listed below, that the project proponent is encouraged to organise a meeting of key stakeholders at an early stage of project preparation. The aims would be to deliberate on the practicalities of achieving a realistic outcome for the project, report back to the GEF and partner agencies on the lessons learned, and develop the project proposal accordingly. The group of stakeholders to be consulted for a project should include:

- representatives of research organisations specialising in the circular economy concept;
- private sector enterprises with direct investment in commercialising the technologies or systems in question;
- farmer, food processor, food retailer or waste management associations as appropriate;
- a social scientist if behavioural changes by consumers are involved in the project;
- financial organisations if a price on carbon, green bonds, quotas, or other economic instruments are involved in the project; and
- specialists in land use, water, energy, climate mitigation or adaptation as required.

For each of the following strategies, some general recommendations from STAP are also provided.

(i) Closing the nutrient cycle

The export of nutrients from farmlands in raw food products and co-products reduces the fertility of soils which threatens future productivity and food quality. Maintaining soil nutrient levels by applying mineral fertilisers is common practice but can result in negative consequences for the environment. The amounts of nitrogen and phosphorus released have already breached planetary boundaries[48]. For example, more than 400 dead zones have been formed in the oceans, such as in the Gulf of Mexico as created by fertiliser run-off from the Mississippi River's watershed[49].

Manufacturing mineral fertilisers usually involves high fossil fuel inputs. Novel methods are under evaluation which have lower GHG emissions, such as using renewable electricity to produce hydrogen that is then used to produce ammonia[50].

Returning nutrients to soils from animal manures, compost, or recovered elements (Fig. 1b)[51] reduces the requirement for chemical fertilisers, minimises sewage treatment, and reduces pollution. Compost made using food wastes from supermarkets, restaurants and households, and organic matter from crop residues, food processing by-products, sewage sludge and effluent outputs can be incorporated into the soil.

Growing leguminous crops that fix atmospheric nitrogen for plant uptake and use, and encouraging free-living nitrogen fixers in the soil, can reduce the demand for artificial nitrogenous fertilisers whilst maintaining crop productivity. Beneficial microbes can provide other positive impacts on soil systems.

Wherever appropriate, relevant programs of the GEF could encourage the recycling of nitrogen, phosphorus, potassium, other minerals and micronutrients currently lost in urban landfills and sewage treatment plants. Farming systems would be managed so as not to 'leak' nutrients and any food processing or consumer wastes remaining after efforts are made to avoid them could be re-processed.

(ii) Reducing competition for productive land

It has been estimated that the world's present productive land of 1540 million hectares (Mha) will need to increase by between 21 to 55% (320 to 850 Mha) by 2050 to satisfy growth in demand for food. The land area available would also need to accommodate competition for the production of fibre, biofuels, and bio-materials, and compensate for land lost to urban development and soil degradation[52]. However, this would then exceed the total area farmed of 1,640 Mha estimated by UNEP to be within the "safe operating space".

Improving productivity in the agri-food sector offers global environmental benefits but also some unique challenges. Past decades have seen a steady increase in crop and livestock productivity as a result of better management, improved seed genotype quality, and animal breeding. However, the annual rate of increase is beginning to slow in many regions, and the land resource base is also declining due to soil degradation.

Project evaluation criteria used by the GEF may need to recognise the potential problems from increased intensification. However, employing circular economy principles can reduce competition for land, for example, through the hydroponic culture of vegetable crops. By-products from food and fibre crops could be used to produce bioplastics or biofuels. Restoring or rehabilitating degraded land can provide additional productive land area for growing food crops. In addition, cutting the volumes of food losses and wastes will reduce the pressure for agricultural expansion, as well as lower the demand for inputs of energy, fertiliser, and water.

The increasing demand for agricultural land can be reduced by further intensifying farming systems to improve productivity (in terms of kg protein per animal or t/ha of crop) but without increasing environmental impacts. The system of crop intensification (SCI) is an example (Box 1)[53]. However, further intensification of some crop and livestock enterprises could also exacerbate local and global environmental impacts unless subjected to careful management.

(iii) Reducing freshwater use by constraining demand

Withdrawal of freshwater from lakes, rivers, and aquifers is now around 4,500 billion m^3 per year, with agriculture consuming nearly three-quarters of that (excluding direct rainfall on non-irrigated land). Globally, demand for freshwater is projected to increase by more than 50% by 2050, with agricultural demand increasing by 20%[54] or more. Freshwater shortages are already occurring due to adverse climate impacts, depletion of aquifers and rivers, and contamination of water sources especially in Africa, the Middle East and South-East Asia (Fig. 2). Many countries have shifted from being designated as 'water-abundant' to 'water-scarce' because of the increased demand for water, as a result of climate change and population growth.

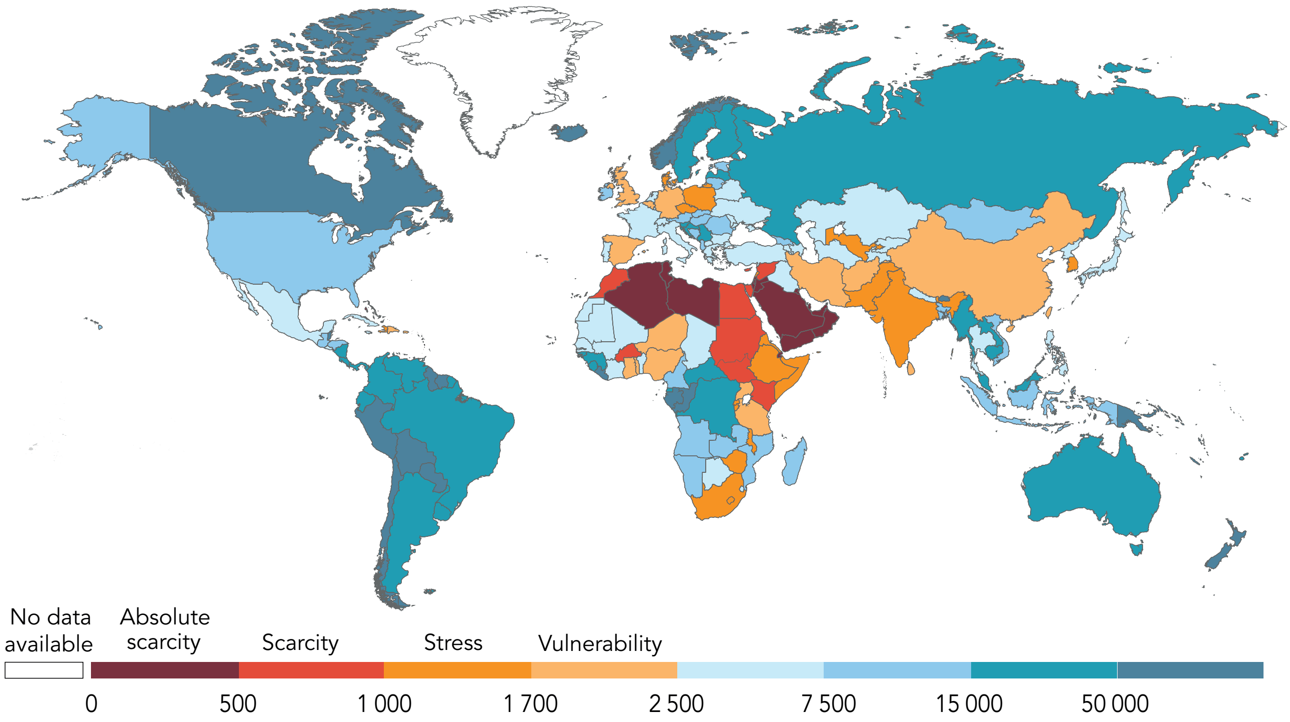


Figure 2. Total freshwater resource availability per capita by country in 2013[55].
Note: scale is non-linear.

Implementing "smart irrigation" schemes, conserving water[56], improving water catchment systems, recharging aquifers, and avoiding pollution of waterways will benefit many farmers and food processors. In countries where water supply and use are subsidised, efforts to conserve water are less likely to succeed. Conversely, the market pricing of water has resulted in more efficient use in Australia and elsewhere, and this model could be followed by others. Alternative sources of freshwater from desalination plants and crop fogging systems, and recycled grey water from buildings, food processing plants, wastewater treatment, urban stormwater etc. could all be used for intensive horticulture, livestock drinking water, and urban agriculture, where economically viable.

Improving the efficient use of water through precision irrigation, water harvesting and storage, water recycling (including urban and food processing wastewater), and imposing strict controls to avoid water pollution can all help restrict the growing demand for freshwater by the agri-food sector and avoid the need for costly desalination or removal of contaminants.

(iv) Safeguarding agro-ecological systems and soil carbon

Under many conditions, agro-ecological practices can compete with conventional farming practices on crop yields but in addition can deliver ecosystem benefits such as healthier soils, rainfall retention, aquifer recharge, removal of contaminants, and reduced run-off[57].

Improving crop productivity, and reducing GHG emissions without substantial investment being required, may be possible by using an agro-ecological approach that encourages low-input organic production of crops and animals, conservation tillage, crop rotations, and integrated crop/livestock systems. Where crop residues and animal wastes can be recycled to the land, soil losses from wind and water erosion are reduced, (but not always eliminated), and the soil carbon content increased.

Farm management systems based on conservation farming can increase agro-eco diversity, improve crop and animal health and provide greater resilience. In addition, a "landscape approach" to managing productive agricultural land can achieve social and economic objectives whilst meeting environmental and biodiversity goals[58].

Soil carbon sequestration at scale is feasible using a variety of measures including:

- rotational grazing and agro-forestry systems;
- replacing annual crops, particularly for animal feed, with perennial alternatives that store carbon longer-term in root systems;
- application and soil incorporation of biochar produced from sustainable sources; and
- a variety of land and vegetation restoration practices, including re-wilding.

There are good opportunities to make agro-ecological systems, and the services they provide, more sustainable in the long term by enhancing their resilience to climate change and hence reducing the negative impacts of modern intensive food production. Any practices known to increase soil carbon contents would be worthy of support by the GEF.

(v) Promoting diversity through agro-ecological practices in agricultural systems

The diversity of genes, species, communities, and landscapes is a critical factor in enhancing the value of agricultural food production systems as are landscapes for ecosystem services, wildlife habitat, climate resilience, and disaster risk reduction. Agro-ecological practices can benefit farm households and rural communities, as well as ecosystem services and biodiversity. They can complement natural habitat management, achieve increased productivity goals, and help promote healthier and more sustainable food and fibre products at local markets.

The GEF should encourage diversification of agro-ecosystems by facilitating access to new seed varieties and supporting innovations that facilitate the marketing of a wide range of food products from local farms and communities.

(vi) Deploying low-carbon, climate-smart technologies

Energy-smart food production systems have been assessed at all scales in both developing and developed countries[59]. Access to renewable electricity and heat allows farmers and food processors to adopt new technologies and so increase productivity, food quality and hence add value to their products.

Other climate-smart mitigation technologies have potential to reduce GHG emissions in agri-food systems. These include solar water pumping, conservation tillage, efficient solar-powered cold storage systems, and drip irrigation. A methodology has been developed[60] to enable decision-makers to make informed decisions when prioritising investment in the many climate mitigation technologies and practices available for deployment along the food supply chain. The technical parameters, financial and economic feasibility, local community benefits, and sustainability of these and other technologies and practices are accounted for when considering the mitigation potential under local conditions. Barriers which may hinder the adoption of specific climate-friendly technologies have been identified and policies have been proposed[61] to remove them and stimulate market penetration.

The UN Food and Agricultural Organisation (FAO) has also undertaken a broad analysis of applying renewable energy technologies in the agri-food sector, using milk, rice and vegetable value-chains as examples[62]. The costs and non-economic benefits have also been evaluated[63]. These include improved human health, saving of time, reduced drudgery, water saving, increased productivity, improved soil quality and fertility, biodiversity protection, improved livelihoods and quality of life, and gains in food security. Trade-offs need to be taken into account when developing policies to encourage the uptake of these technologies.

Many opportunities exist to improve energy efficiency throughout the food supply chain, including on-farm, transport, and processing. Deploying renewable energy systems is feasible along the entire food-chain. Proven climate-smart technologies that have a range of co-benefits should be promoted where appropriate.

(vii) Reducing the demand for animal protein

The global demand for animal protein is growing. Reducing animal protein intake per capita, especially in affluent and urbanised societies, by substituting vegetable protein would not only reduce GHG emissions and the demand for land and water, but could also improve human health. Consumer demand is the key driver of the food sector, so heightened awareness of these issues could be a key step to making behavioural changes. However, in some regions, for traditional communities where meat is a high-quality form of dietary protein and wild meat is traded, livestock production can have cultural and economic significance. Also in drylands and cold regions, there may be no viable alternative productive use of land.

To produce a unit of animal protein uses significantly more land, water, and energy than a unit of vegetable protein. Providing protein from other sources where feasible also uses fewer resources per unit than when producing animal protein. As a circular economy principle, protein demand could probably be met by low input alternatives including those derived from pulses, vegetables, insects, and biological and chemical synthesis. These alternatives also impact less on biodiversity and ecosystem services than when producing animal protein, although the differences are still to be quantified[64].

There is a growing trend towards producing synthetic protein biochemically and several companies are developing and retailing such products[65]. For example, this “meat” can be grown cleanly and efficiently under factory conditions by fermentation of vegetable proteins or from just a few stem cells. These synthetic food products are claimed to be able to supply all human nutritional needs, including vitamin B12 which is mainly found in animal products. If the energy inputs for such a process can be met from renewable sources, the carbon footprint is much lower than from farming animals[66] and demand for water and soil nutrients are also reduced.

Innovative techniques to produce food products from synthetic proteins are rapidly becoming commercialised. Such developments should be supported and promoted by the GEF to reduce demand for animal protein and offset the environmental impacts resulting from animal production for meat and milk products.

(viii) Producing food within the urban landscape

Rooftop gardens, community vegetable plots, and living building facades are becoming common in cities worldwide. They could provide significant volumes of local food for the citizens in the near term. Multi-storey “factory farms” (known as “vertical farming”) are more long term, although demonstration plants already operating in some cities are claimed to achieve about 70 times the food intensity per unit land area compared with field crop production[67].

Since urban citizens consume (or waste) more than half of total food nutrients and a quarter of total freshwater demand, cities could become a major enabler of the circular food economy by capturing and reusing these resources for urban food production.

Integrating the management of food production activities within urban locations can help meet the disaster risk management, biodiversity and climate goals of a city as well as reduce water demand and improve water quality[68].

Encouraging the development of urban food production should be supported, for example as a component of the GEF/World Bank's Sustainable Cities IAP.

(ix) Promoting advanced innovative technologies

Radical changes to global food production systems during the next decade could include the rapid development of novel practices and technologies[69] such as robotics, advances in biotechnology, genetic modification, artificial intelligence, virtual reality, and big data analysis.

New and near-commercial technologies include:

- monitoring soils and crops remotely;
- precision farming systems that apply fertiliser, agri-chemicals, and water only when and where needed;
- drones that apply agri-chemicals precisely and can also be used to check the health of crops and livestock;
- cows milked robotically whenever they choose to be without human intervention;
- smartphones used by farmers to help diagnose crop disease, receive expert advice, and check market prices;
- energy efficient storage facilities and refrigeration systems, including solar absorption technologies;
- crops grown in non-soil media under a controlled environment in urban locations using diverse, highly technical, indoor ecosystems; and
- renewable heat and electricity generated for use on-site by small and large-scale farms as well as food processors.

Many innovations not yet commercially viable but reaching the demonstration phase could prove beneficial for making the food supply system more sustainable in the long-term.

The GEF should assess the relevance, impact, and sustainability of these technologies for different types of food systems (e.g rice, milk, vegetables); support their adoption where needed; and monitor the environmental costs relative to the potential benefits for farmers, food processors, and consumers.

(x) Stimulating policy and institutional advances

Transforming agri-food production and consumption systems and mainstreaming the circular economy will require cross-sectoral collaboration, the inclusion of the private sector, leverage of private financing and capacity building. A number of organisations have recently developed a strong involvement in working towards a circular economy in the food sector. For example, the Ellen Macarthur Foundation in the UK has initiated a major analysis of the concept linking food supply with cities[70].

The GEF could play a catalytic role by supporting enabling activities to develop a better alignment between the agri-food sector and environmental management. It could provide incentives for cross-sectoral collaboration and develop partnerships with the private sector and other interested organisations. In addition, it could assist recipient countries to develop and adopt suitable policies and provide them with incentives to support demonstration projects of novel technologies, systems and institutional innovations suited to the prevailing circumstances of the agri-food sector.

(xi) Measuring success

The potential environmental benefits per unit of food product delivered to the consumer are complex but can be measured in terms of units of water or fossil fuel energy inputs consumed, amount of GHGs emitted, nutritional quality, and food losses and wastes avoided (in terms of total production per unit of product finally consumed). A full range of indicators to measure project success has been proposed by U.N. Environment's International Resource Panel[71]. In addition, the Food Sustainability Index[72] identified 58 indicators used to assess, compare, and rank how a country's food supply system, and its stakeholders, are moving towards greater sustainability. However, the present suite of indicators is relatively weak on ecosystem services, climate impacts, land health and biodiversity measures, as well as evaluation within complex landscapes.

The GEF could play a leadership role in strengthening and encouraging the use of metrics that not only address environmental impacts per unit of agricultural output, but also track the overall health of agricultural landscapes in terms of production, productivity and ecosystem services, biodiversity, food security and human well-being.

Conclusion

The global food supply system and the land/water/energy/climate nexus are complex. Currently, the global food supply system is not sustainable. The GEF's integrated programs that relate to the future sustainability of food supply should be monitored to ensure that potential solutions to reducing environmental impacts, including promoting the circular economy approach and any trade-offs, are well understood. Given the rapid rate of technological development and growing consumer awareness, any future interventions by the GEF should be supported by the latest scientific knowledge.

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