AGRICULTURE AND FOOD SERIES

OVERVIEW

# Insect and Hydroponic Farming in Africa

## *The New Circular Food Economy*

Dorte Verner, Nanna Roos, Afton Halloran, Glenn Surabian, Edinaldo Tebaldi, Maximillian Ashwill, Saleema Vellani, and Yasuo Konishi

WORLD BANK GROUP

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Different forms of insect farming and soilless crop farming, or hydroponics, have existed for centuries. In this report the authors make a persuasive case that frontier agriculture, particularly insect and hydroponic farming, can complement conventional agriculture. Both technologies reuse society's agricultural and organic industrial waste to produce nutritious food and animal feed without continuing to deplete the planet's land and water resources, thereby converting the world's wasteful linear food economy into a sustainable, circular food economy.

As the report shows, insect and hydroponic farming can create jobs, diversify livelihoods, improve nutrition, and provide many other benefits in African and fragile, conflict-affected countries. Together with other investments in climate-smart agriculture, such as trees on farms, alternate wetting and drying rice systems, conservation agriculture, and sustainable livestock, these technologies are part of a promising menu of solutions that can help countries move their land, food, water, and agriculture systems toward greater sustainability and reduced emissions. This is a key consideration as the World Bank renews its commitment to support countries' climate action plans.

This book is the World Bank's first attempt to look at insect and hydroponic farming as possible solutions to the world's climate and food and nutrition security crisis and may represent a new chapter in the organization's evolving efforts to help feed and sustain the planet. We hope the book will ignite further discussions and inspire concrete actions toward fully capturing the vast opportunities provided by insect and hydroponic farming as part of revamped, high-performing food systems that provide healthy and sustainable diets for all.

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# FOREWORD

The mission of the World Bank is to end poverty and improve equity through shared prosperity. But hard-fought development gains are now under threat. Every day there are signs of deepening climate change, dwindling natural resources, and intensifying food and nutrition insecurity, amid a global pandemic that has challenged people's ability to afford a healthy diet.

Interestingly, some relief from today's woes may come from ancient human practices. While current agri-food production models rely on abundant supplies of water, energy, and arable land and generate significant greenhouse gas emissions in addition to forest and biodiversity loss, past practices point toward more affordable and sustainable paths.

Different forms of insect farming and soilless crop farming, or hydroponics, have existed for centuries. In this report the authors make a persuasive case that frontier agriculture, particularly insect and hydroponic farming, can complement conventional agriculture. Both technologies reuse society's agricultural and organic industrial waste to produce nutritious food and animal feed without continuing to deplete the planet's land and water resources, thereby converting the world's wasteful linear food economy into a sustainable, circular food economy.

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*World Bank Group*

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# OVERVIEW

This report shows that frontier agriculture is a viable complement to conventional agriculture, particularly in Africa and countries affected by fragility, conflict, and violence (FCV). The purpose of the report is to increase knowledge on food and nutrition security in Africa and present innovative solutions to address this challenge. The report assesses the benefits of expanding frontier agricultural technologies within a circular food economy in Africa, with a focus on FCV-affected countries. Frontier agricultural technologies include insect farming and plant hydroponics, both of which quickly produce nutritious food and feed and can improve food and nutrition security, reduce waste and greenhouse gases (GHGs), and promote green, resilient, and inclusive development. Neither the consumption of insects nor hydroponic crops is new—humans have been consuming both for many years. However, farming insects and hydroponic crops to achieve development goals is a new and innovative approach, especially for vulnerable communities—Africa is home to 40 percent of the world's forcibly displaced persons (UNHCR 2020)—who have limited resources and live in extreme climates that rarely support conventional farming. Insect and hydroponic farming can be applied in a circular food economy, which is a food production model that uses organic waste, including agricultural and industrial waste, to produce nutritious food without the need for arable land or abundant supplies of energy and water resources. These industries have great potential for growth and scalability and are cost-effective compared with conventional agriculture in resource-constrained environments. Estimates show that the market for farmed insects for human food and animal feed will be worth up to US$8 billion by 2030, with a 24 percent compound annual growth rate (CAGR) (MarketWatch 2019). The market for hydroponics was worth about US$9.5 billion in 2020 and projected to grow at a CAGR of 11.3 percent, reaching US$22.2 billion by 2028 (Intrado 2021).

This assessment finds that there are tremendous health, social, economic, climatic, environmental, and food and nutrition security benefits to adopting frontier agriculture in Africa. These frontier agricultural technologies work within a circular food economy to reuse society's waste to produce nutritious food for humans, fish, and livestock. The report proposes using these technologies—specifically insect farming and hydroponics—to increase access to protein and other vital nutrients among food insecure populations in African countries affected by FCV. Such technologies can build the food system's resilience to shocks such as the COVID-19 (coronavirus) pandemic, climate variability, and other crises. They can also reduce malnutrition; create climate-resilient jobs, incomes, and livelihoods; save hard currency and reduce current account deficits in FCV countries by producing rather than importing protein for human food and animal feed and fertilizers; and reduce the environmental risks—such as deforestation, soil degradation, and biodiversity loss—associated with current agri-food production models in a linear food economy. The report finds that only heavily disruptive, inclusive, and resilient food production models have the potential to meet Africa's dire and wide-ranging food and nutrition security challenges.

African insect farming could generate crude protein worth up to US$2.6 billion and biofertilizers worth up to US$19.4 billion. That is enough protein to meet up to 14 percent of the crude protein needs for all the pigs, goats, fish, and chickens in Africa. The report determines this by modeling the production levels and benefits from farming black soldier fly larvae (BSFL) in Africa using 30 percent of the waste from five of the most common crops on the continent. The modeling estimates that through black soldier fly farming, the continent could replace 60 million tons of traditional feed production with BSFL annually, leading to 200 million tons of recycled crop waste, 60 million tons of organic fertilizer production, and 15 million jobs, while saving 86 million tons of carbon dioxide equivalent ($CO_2$-eq) emissions, which correspond to removing 18 million vehicles from the roads. Box O.1 summarizes the report's research methodology.

## JUSTIFICATION

Food and nutrition insecurity is high and rising in Africa, especially in FCV countries. In Africa, food systems already faced long-term challenges before COVID-19. After several years of decline, the prevalence of acute food and nutrition insecurity is on the rise in Sub-Saharan Africa, where about one in five people is undernourished (FAO et al. 2019). Since 2014, per capita food production has been falling on the African continent.[1] An estimated 121 million people, or 24 percent of the population, consume less food than they need for a healthy life. The situation is worse in FCV countries (figure O.1)[2] where 29 percent of the population experiences insufficient food consumption, compared with 18 percent of the population in Sub-Saharan Africa overall. Moreover, hunger is not the same in all FCV countries. For

## BOX O.1 Summary of Research Methods

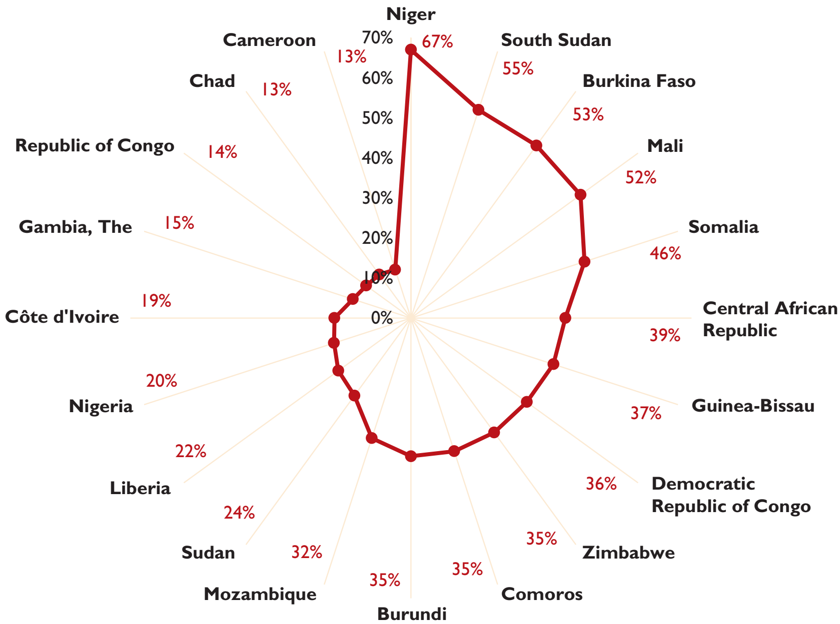
This report relies on original research and a literature review on themes related to food and nutrition security, insect farming, and hydroponics in Africa, including countries affected by fragility, conflict, and violence (FCV). For the report, FCV-affected countries were determined by the World Bank's fiscal year 2021 list of countries in fragile and conflict-affected situations. The original research fills data and information gaps on these themes. The following are the three main research methods:

1. The research team carried out two surveys between September 2019 and January 2020 on insect farming in Africa. The objective of the surveys, one at the country level and the other at the farm level, was to obtain a rapid assessment of insect farming activities in 13 African countries: Benin, Burundi, Cameroon, the Democratic Republic of Congo, the Arab Republic of Egypt, Ghana, Kenya, Madagascar, Rwanda, Tanzania, Tunisia, Uganda, and Zimbabwe. Four of these countries—Burundi, Cameroon, the Democratic Republic of Congo, and Zimbabwe—are officially designated as being in fragile and conflict-affected situations.
2. The team modeled the frontier agricultural supply chain of black soldier fly larvae (BSFL) production in Africa and, individually, in Zimbabwe and 10 other African countries. The model quantified the food production levels, waste reduction levels, and climatic, employment, and environmental benefits from BSFL production given different crop substrates. The findings are presented in chapter 4.
3. This research was supplemented with qualitative information from field visits to Kenya in May 2019, Zimbabwe in May and August 2019, Thailand in December 2019, and the Republic of Korea in August and December 2019. Asia has more experience with insect farming than any other region in the world. COVID-19 (coronavirus) travel restrictions limited the team's ability to complete planned visits to other FCV countries in Africa.

example, in Niger, Mali, South Sudan, and Burkina Faso, more than 50 percent of the population experiences insufficient food consumption. Chronic undernutrition has stunted one in three children in Sub-Saharan Africa. It is also the leading cause of death for 45 percent of the world's children under age five years, totaling 3.1 million preventable child deaths per year (Black et al. 2013). Figure O.2 shows that undernourishment rates in African FCV countries will continue to rise for at least a decade. The lack of nutritious food affects economic development through declines in childhood development, economic productivity, and people's general well-being.

Lack of effective demand drives the region's food and nutrition insecurity. Effective demand is determined by a household's purchasing power, or its ability to pay for food and other goods and services. Therefore, the lack of demand is driven largely by income poverty and ineffective distribution. In nine of the 20 African FCV countries, 50 percent of the population lives in poverty, with poverty levels reaching 82 percent in South Sudan (World Bank 2020a). Individuals

**FIGURE O.1 Share of the Population in African FCV Countries with Insufficient Food Consumption, 2021**

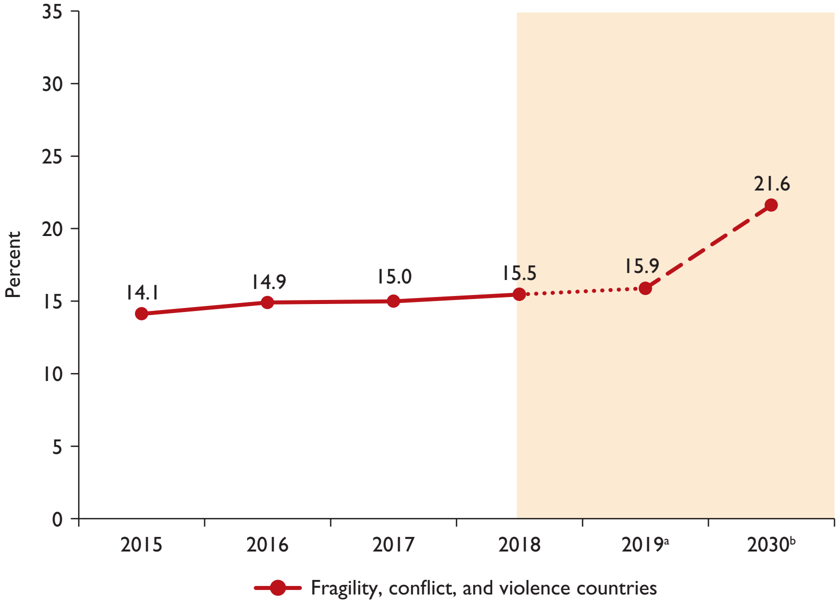



*Source:* Original figure for this publication, using World Food Programme data, January 24, 2021.
*Note:* FCV = fragility, conflict, and violence.

living below the poverty line often cannot afford enough nutritious food to live a healthy life. In Africa, poverty and ineffective distribution (for example, as a result of underdeveloped supply chains and infrastructure) are the largest contributors to food and nutrition insecurity (World Hunger Education Service 2018).

Africa's population growth, land degradation, and climate variability and change also complicate the region's long-term food and nutrition security. With the Sub-Saharan population projected to reach 2.2 billion by 2050 (Suzuki 2019), food access and production needs are increasing significantly. Meanwhile, the African continent contributes relatively little to total global GHG emissions, but it is one of the regions in the world most negatively affected by climate change, which further limits its ability to improve food security (FAO and UNECA 2018). In Africa's FCV countries, increased climate variability is already causing more droughts, floods, and pest attacks, such as the 2020–21 locust emergency. Moreover, average temperatures have risen over the past two decades by more than half a degree Celsius in 17 of 19 African FCV countries.[3] This, together with exploitative conventional farming techniques and declining freshwater resources, has led to increased land degradation and, in some places, aridity in African FCV countries.[4] One study projects that climate change will reduce average crop yields in Africa by 2050, including reducing wheat yields by 17 percent, sorghum by

**FIGURE O.2 Prevalence of Undernourishment in African Fragility, Conflict, and Violence Countries, 2015–30**




*Source:* Original figure for this publication, using World Bank Africa Sustainable Development Policy Unit compilation of data from FAO 2020.

*Note:* The graph underestimates the food insecurity situation as data from some of the most food insecure fragility, conflict, and violence (FCV) countries, such as Niger and South Sudan, are not available and therefore not included.

a. Projected values.

b. Projections up to 2030 do not reflect the potential impact of the COVID-19 pandemic.

15 percent, millet by 10 percent, and maize by 5 percent (Knox et al. 2012). This is reinforced by undernourishment statistics, which show that the number of undernourished people in drought-sensitive countries has increased by 45.6 percent since 2012 (FAO et al. 2019).

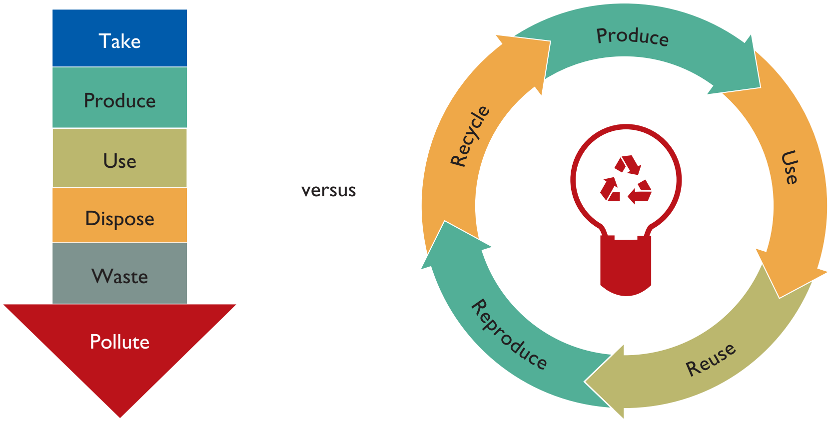
The COVID-19 pandemic and other shocks have exposed Sub-Saharan Africa's food and nutrition insecurity issues. Countrywide lockdowns during the pandemic caused market disruptions and led to job and income losses. For example, in Nigeria, 42 percent of respondents to a phone survey were no longer working, despite being employed pre-COVID-19. In Ethiopia, 45 percent of urban households and 55 percent of rural households reported income losses due to COVID-19 (Dabalen and Paci 2020). More generally, COVID-19 has disrupted food supply chains, which will double acute food and nutrition insecurity, contract domestic food production by 7 percent, and reduce food imports by 13 to 25 percent for African countries, of which 39 countries are already net food importers.[5] Like in most economies, COVID-19-related job losses have been more significant for lower-income and informal workers whose jobs cannot be performed from home. All these impacts are exacerbated by conflict, natural shocks, climate change, natural resource shortages, and agricultural challenges, such as crop and livestock pests and diseases, including the desert locust emergency. Most of these food and nutrition security and poverty vulnerabilities are even worse in Africa's 20 FCV countries.[6]

The world's natural resource base does not have the carrying capacity to sustain the world's current agri-food model, especially for animal feed. Arable land dedicated to the production of feed represents about 80 percent of the world's total agricultural land.[7] The agri-food system accounts for about 30 percent of the world's total energy consumption (FAO 2016), with agriculture, particularly animal rearing, as the most energy-intensive (Jasinski et al. 1999). For example, soy production accounts for about 10 percent of Brazil's deforestation, with three-quarters of soy being fed to livestock as animal feed.[8] Moreover, the agri-food system acquires 80 percent of its energy needs from fossil fuels (Monforti-Ferrario and Pinedo Pascua 2015). Agriculture accounts for 70 percent of the world's freshwater withdrawals (UNESCO 2016), and the figure is even higher in the nine African FCV countries with available data (World Bank 2020a). Aquifers replenish so slowly that they are effectively a nonrenewable resource (Dalin et al. 2017). Studies also show that soil erosion rates under plowed cultivation are twice as fast as soil replenishment rates (Montgomery 2007). This creates a need for fertilizers, of which the vast majority still require fossil fuels to produce (Kudo and Miseki 2009). For example, the global agri-food system uses about 90 percent of the world's extracted phosphorus (Childers et al. 2011). These unsustainable land use practices also contribute to climate change and biodiversity losses, exacerbating food supply challenges even more (World Bank 2020b). This all demonstrates that the world's natural environment will not be able to sustain the global food production model's current levels of natural resource extraction.

## SOLUTIONS

A disruptive, inclusive, resilient, and efficient "circular economy" model for food production could contribute to solving Africa's food and nutrition security and food systems challenges. The world needs an integrated food production system that can feed everyone, everywhere, every day with nutritious food while providing economic benefits, increasing incomes, and protecting the environment—or to put it differently, a system for healthy people, a healthy economy, and a healthy planet. A circular food economy encompasses such a system. It is a systemic approach to food production that is mutually beneficial to businesses, society, and the environment.[9] It is designed to produce food while eliminating waste and pollution. The circular food economy and the traditional linear food economy are shown in figure O.3. The linear economy follows a "take-make-waste" model in which resources are exploited to produce food while generating waste and polluting the environment. For example, about 30 percent of the world's agriculture and food production is lost

**FIGURE O.3 Linear versus Circular Economy for Food Production and Consumption**




*Source:* Original figure for this publication, using Weetman 2016.

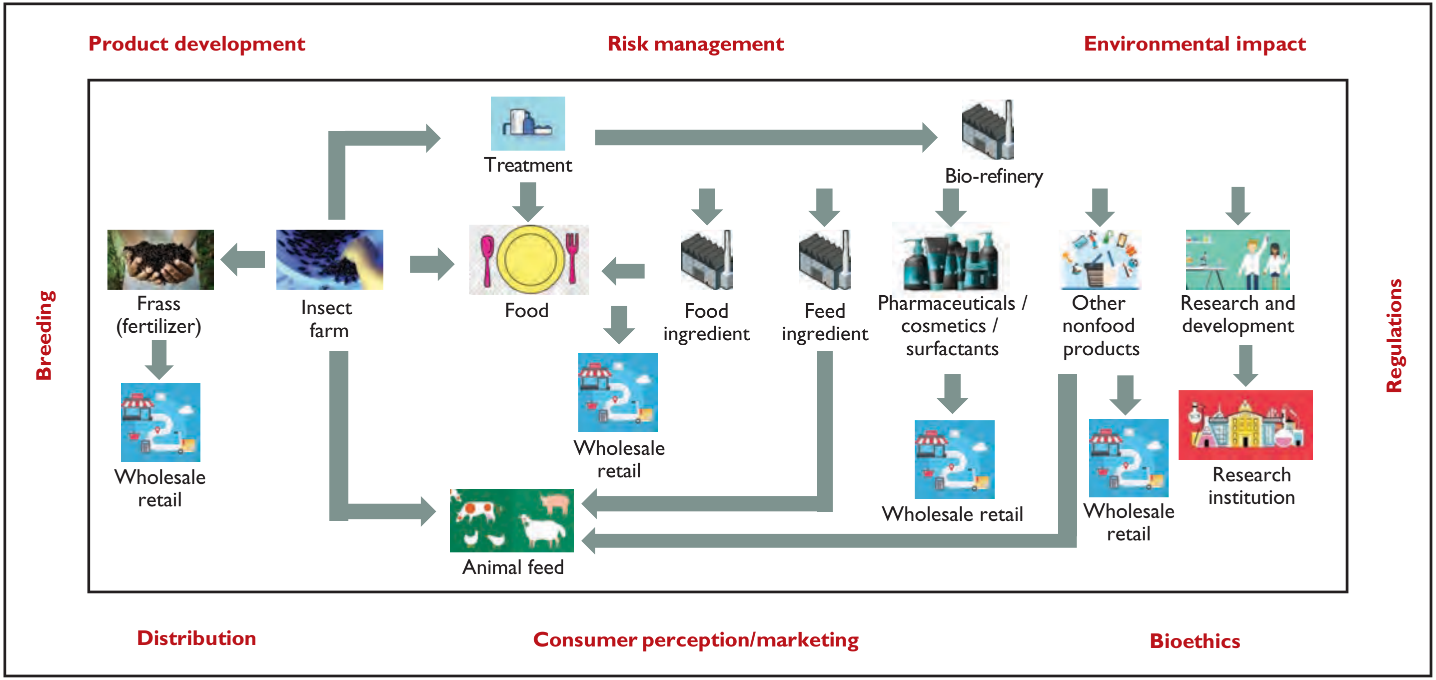
or wasted in the food supply chain (FAO 2014). This model relies on continuous inputs of new resources to produce more outputs, and it has been the dominant model for economic development since the Industrial Revolution. By contrast, a circular economy is regenerative by design. It gradually decouples food production from the consumption of finite resources by reintegrating waste, instead of new resources, as an input into the food production system. With the increasing demand for nutritious food and dwindling natural resources due to climate change and environmental exploitation, a circular economy model is better suited to Africa's food and nutrition security needs than the current linear economy. In sum, a circular food economy can produce food efficiently, create jobs, and replenish the environment without the waste that is typical of a linear economy.

Frontier agricultural technologies can help turn a linear food economy into a circular food economy. Frontier agricultural technologies are sustainable approaches to agricultural production that reuse waste to grow nutritious food and animal feed. Such technologies do not require arable land or significant energy and water resources. These technologies contribute less to GHG emissions than does conventional agri-food production and have a limited impact on the environment. Two examples of frontier agriculture are insect farming and hydroponic crop farming. These two disruptive technologies are the focus of this report (see figure O.7 for a visual depiction of the circular food economy and how frontier agriculture fits within it). Insect farming is the process of producing insects for use in human and animal diets. As the report shows, insects can be a source of valuable proteins and essential micronutrients. Insect farming can even reduce existing human or industrial waste from the linear economy by using organic waste as feed for farmed insects. Hydroponics is the process of growing plants in nutrient-rich water, instead of soil. Both technologies are alternatives to the prevailing food system and are a natural fit for the unique context of African FCV countries. Both systems use space and water efficiently, are cost-effective, and require less labor than conventional crop or livestock production. In addition to their food production benefits, these technologies can also create economic opportunities in rural and urban areas and provide livelihoods, including for vulnerable populations, such as youth, women, and refugees. The report does not focus on other promising frontier agricultural technologies—such as algae farming, permaculture, and others—because they likely require more water or arable land than is typically available for vulnerable communities in African FCV countries.

Insects are part of traditional diets in Africa, and the insect farming industry for human food and livestock feed is growing (van Huis 2017, 2020; Niassy et al. 2018). More than 20 percent of the 2,100 insect species recognized as edible worldwide (Jongema 2017) are consumed in Africa (Kelemu et al. 2015). People in Africa have collected insects from the wild for consumption for thousands of years, although the farming of insects is much more recent. Some of the notable insects consumed on the continent, and described in this report, include fly larvae, crickets, mealworm, and palm weevil larvae. Two insect species in particular have a long history of domestication: the honeybee for honey and the silkworm for silk. Among African FCV countries, the Central African Republic, the Republic of Congo, the Democratic Republic of Congo, and Zimbabwe are the largest consumers of insects (Niassy and Ekesi 2017). For example, 90 percent of Zimbabwe's population has consumed insects, with termites and mopane caterpillars being the most common (Dube et al. 2013). In other countries, the history of insect consumption varies among ethnic groups. In Kenya, coastal communities historically have consumed few or no insects (Kelemu et al. 2015), while the Luo population in western Kenya, for example, consumes insects such as termites and lake flies. However, traditional insect foraging is rapidly declining among younger generations (Ayieko and Oriaro 2008).

This report's country-level survey reveals that insect farming occurs in 10 of the 13 surveyed countries at different scales. The country-level survey identifies 849 insect farms of various sizes in those 10 countries, although, according to the surveyors, the total number of farms is closer to 1,800. And a market for insects and insect-based products already exists in Africa. For example, in Southern Africa, mopane worms are traded in local markets and across borders. Experience outside the region shows that strong market growth is possible with the right kind of support. In the Republic of Korea, in less than a decade, the insect farming industry has advanced, in part by developing public and private partnerships to carry out training, financing, and research and development, among other actions. By late 2019, Korea had more than 2,500 insect farms producing insects for food, feed, health, and medicinal products (MAFRA 2019). Each year, the number of new entrants, companies, and initiatives around the world increases. These small- and large-scale producers and commercial producers frequently operate within similar geographic regions without undermining one another, and they often complement one another. Figure O.4 presents a rough representation of the value and supply chain of farmed edible insects.

**FIGURE O.4** **Rough Representation of the Farmed Edible Insect Value and Supply Chain**




*Source:* Adaptation of Peters, undated.

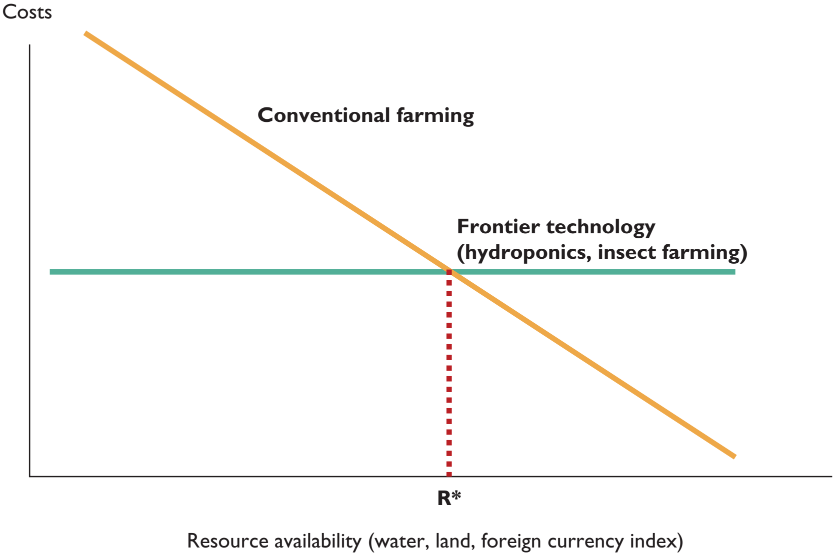
Hydroponics is an expanding practice that can grow crops quickly without soil. Growing plants in nutrient-rich water has been practiced for centuries. Early examples of hydroponic growing include Babylon's hanging gardens and the Aztecs' floating gardens in Mexico. In traditional farming, soil stores the various nutrients required for plant growth. When water saturates the soil, the water picks up these nutrients and is absorbed by the plant's roots (Campbell and Reece 2002), moving to the plant's shoots, leaves, and fruit. In hydroponics, the need for soil is removed by feeding the nutrient-rich water directly to the plant. As this report shows, hydroponic farming is increasingly becoming an important crop production technology in FCV contexts, including refugee camps and arid host communities in East and West Africa. For example, hydroponic systems are used to produce animal feed in Chad and human food in Kenya, Sudan, and Zambia.

## VIABILITY

Frontier agricultural technologies have a cost advantage over conventional agriculture when resources are constrained. Figure O.5 shows the threshold at which these technologies become more cost-effective. The figure shows stylized cost curves for frontier farming and conventional farming. In the figure, $R$ is a resource index that includes natural resources—such as water, nutrients, and arable land—and economic inputs—such as hard currency and feed or infrastructure inputs. It shows a direct advantage for frontier agricultural technologies when resources are constrained, or when $R$ is less than or equal to the tipping point level of resources, or $R^*$ ($R \leq R^*$). This is why these technologies have found success in hard currency–constrained economies and arid or densely populated areas, including in refugee camps and near crowded cities. This also explains why frontier agricultural technologies are already monetarily advantageous alternatives to traditional agriculture in the resource-poor communities that are prevalent in Africa and FCV countries.

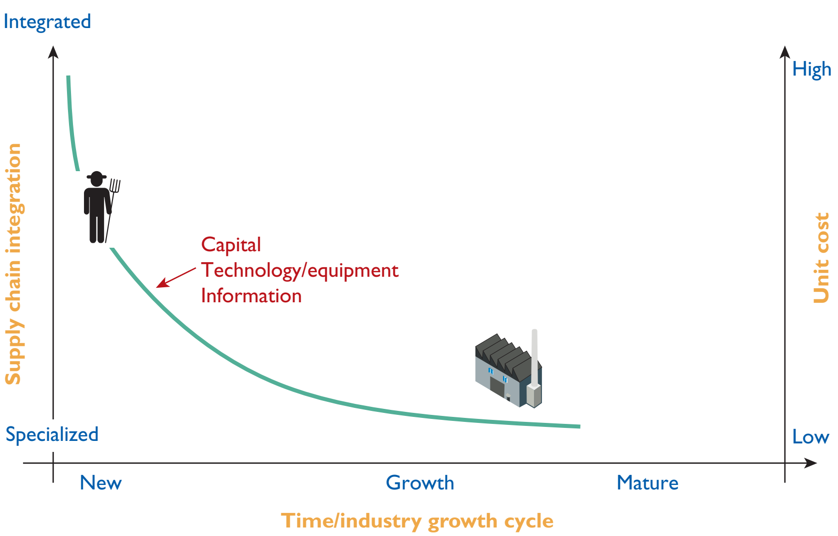
Frontier agriculture becomes even more cost-effective as these technologies are scaled up and processes become more specialized. In an integrated, or nonspecialized, production system, an individual producer carries out all the steps in the production process. In a specialized system, specialists carry out the steps separately according to their relative skills or comparative advantages. As such, the cost per unit in a specialized system is lower than in an integrated system (figure O.6). As the production systems reach scale, they are more likely to be specialized systems. Conversely, small-scale artisanal operations are more likely to be integrated and have higher marginal costs. These costs are largely determined by the system's access to capital, information, and technology and equipment. Moreover, as frontier agriculture becomes more prevalent and systems begin to scale, there will be a greater likelihood of technological advancements, process innovations, and investments in research and development, which will

**FIGURE O.5 Comparative Advantage of Frontier Technology Relative to Conventional Farming When $R \leq R^*$**




*Source:* Original figure for this publication.

**FIGURE O.6 Supply Chain Integration versus Costs over Time**




*Source:* Original figure for this publication.

bring down costs, lowering the horizontal cost curve in figure O.5 even more. Insect farming and hydroponics offer realistic prospects for scalability given each industry's growth potential and conventional farming's large and growing demands for arable land, energy, and water resources.

Farming subsidies reduce the cost of conventional farming, which could impede the transition to frontier agriculture and the circular food economy. These policies distort cost incentives and lower the conventional farming line below the unsubsidized cost line in figure O.5. These types of subsidies are called policy errors of commission and occur when governments subsidize or give preferential treatment to environmentally harmful alternatives. Examples include subsidies that promote an overreliance on irrigation or excessive use of fertilizer. Meanwhile, missing policies, or policy errors of omission, can be equally damaging. These occur when governments fail to take corrective action to mitigate the damaging impacts from conventional farming and the linear agri-food production model. Such bad policies, from errors of commission or omission, can create disadvantages for new technologies that are socially and environmentally preferable. If governments corrected any of these policy errors, there would be a shift in the comparative and competitive advantages of frontier agricultural technologies relative to conventional farming, causing outward movement of the conventional farming line in figure O.5.

The private sector has already determined that frontier agriculture is viable and, globally, the race is on to invest in insect and hydroponic farming. Overall, investment in agricultural start-up companies grew to US$5.1 billion by 2020 and is expected to increase another 25 percent by 2022. In the first six months of 2021, there was US$4.3 billion in new investments in the agriculture sector across 263 deals (Welborn 2021). Much of this capital is going toward frontier agricultural technologies. For example, large companies and suppliers in the agri-food sector—such as the Bühler Group (2019), Cargill (Byrne 2018a), Wilbur-Ellis (2018), and McDonald's (Byrne 2018b)—are increasingly investing in novel insect-based proteins as feed sources. Moreover, venture capital firms are investing heavily in frontier agricultural technologies. For example, in Europe, Astenor Ventures invested US$372 million in Ynsect, a commercial insect producer in France (Law 2020; Reuters 2020). In 2020, the hydroponic and indoor agricultural industry raised US$565 million in new investments. From 2016 to 2017, venture capital funding for vertical farming increased from US$36 million to US$271 million, a 753 percent increase. Most of this frontier agricultural investment goes to companies in high-income countries, although there are increasingly examples of frontier agricultural investments in Africa. For example, as of 2018, the South African insect protein firm AgriProtein had raised US$105 million for black soldier fly larvae production (AgriProtein 2018). It is not difficult to understand why. The insect protein industry is predicted to grow at a CAGR of 24 percent until 2030 (MarketWatch 2019) and the hydroponics industry at a CAGR of 11.3 percent until 2028 (Intrado 2021).

## BENEFITS

Frontier agricultural technologies produce nutritious food that could combat hunger in Africa. Edible insects provide a highly digestible protein, a fundamental component for all biological systems. The protein quality of insects provides the essential micronutrients and amino acids for human nutrition. Insects also provide fats and important micronutrients, especially zinc, iron, and calcium, which are often deficient in food-insecure populations. However, the supply of insects collected in nature is traditionally seasonal (van Huis 2005). And wild insects can feed on trees and crops that have been sprayed with dangerous pesticides. Farming insects can overcome these challenges by providing a continuous and year-round nutrient and protein source from a controlled feeding process. There is also promising evidence that using insects for animal feed improves animal health and nutrition. For example, modeling carried out for this report shows that the protein content of farmed insects, particularly BSFL, compares favorably with the protein content of soy cake (47 to 49 percent) (Heuzé, Tran, and Kaushik 2020) and groundnut cake (45 to 60 percent) (Purohit and Rajyalakshmi 2011), two common types of animal feed. The modeling also projects that Africa could produce 60 million tons of BSFL if 30 percent of countries' crop waste was used for substrate. Hydroponics grow produce with similar amounts of nutrients as conventional soil-grown produce. Since plants generate their own vitamins by absorbing nutrients and converting sunlight into energy, there are no differences in vitamin levels among plants grown in soil or in nutrient solutions. However, in hydroponic systems, simply adding nutrients to the solution can enhance a plant's nutrient levels. These nutrients could include calcium, magnesium, or essential trace elements such as zinc or iron. Thus, hydroponics can more efficiently produce nutrient-rich foods than can soil-based agriculture. The protein- and nutrient-rich content of frontier agriculture–based foods could help improve Africa's high levels of stunting and undernutrition.

Frontier agriculture can supplement incomes and create climate-resilient jobs. In Cameroon, the average income of formal African palm weevil larvae collectors varies between US$180 and US$600 per month, which is 30 to 75 percent of their household income (Muafor et al. 2015). Incomes from palm weevil sales are significantly higher than the incomes of unskilled workers or rural coffee producers (Muafor et al. 2015). In Ghana, economic viability analyses show that African palm weevil farmers could pay back their initial capital investment in weevil farming in 127 days. In a year, a farmer could have three production cycles and generate US$553 in revenue by selling 755 larvae per month. This would produce a net cash availability of US$265 and a net profit of US$82 in the first year of production. Experience from other regions corroborates the economic potential of frontier agriculture technologies. In Thailand, small-scale cricket farming has diversified rural household incomes, and their average incomes can be significantly more than those for other agricultural activities, especially in the northeastern part of the country (Halloran, Roos, and Hanboonsong 2017). In Korea, insect farming revenues vary greatly according to insect species, but they are higher than minimum wage earnings. Insect farming revenues can be increased further by processing the insects into dry insects; protein flour, used, for example, for crackers, bread, or porridge; or any number of products. The profitability of hydroponics increases when it is used to produce high-value crops, such as fruits and vegetables rather than grains, and value-added products or raw produce that has been modified or enhanced to have a higher market value. For example, basil can be processed into pesto, tomatoes into tomato paste, fruits into jam, and herbs into essential oils. Small-scale frontier agriculture also allows time for other profitable activities. For example, in Thailand, small- and medium-scale cricket farmers spend fewer than three hours per day tending to their crickets, leaving time for other income-generating activities (Halloran, Roos, and Hanboonsong 2017). This report's modeling finds that BSFL production could create more than 4 million direct employment opportunities and more than 11 million indirect employment opportunities in Africa. This means that production of BSFL could generate more than 15 million jobs on the continent.

> *Insect farming serves as a secondary income generation activity for me. Consulting on insect farming alone gives me almost half of my annual salary as a government employee.*
>
> *—Ghanaian farmer*

Hydroponics uses less water and has higher crop yields and faster growth rates than conventional agriculture. A pilot hydroponics project in Kakuma Refugee Camp in Kenya showed that hydroponics used between 82 and 92 percent less water than conventional farming for growing kale, spinach, and cowpeas. One circular garden and two hydro crates, which together require four square meters of land, produced 2,780 grams of spinach, compared with 188 grams of spinach for a conventional farm using the same amount of space. That is 15 times more produce in the hydroponics system. Meanwhile, one hanging garden, which accommodates 64 plants, produced 446 grams of spinach, whereas the conventionally farmed plot, which accommodates 89 plants, produced only 200 grams of spinach.

Frontier agriculture is not associated with any particular age or gender, but it could provide benefits to youth, women, and vulnerable populations. The farm-level survey shows that 12 percent of insect farmers are younger than 30 years, and 22 percent are older than 60. Historically, wild insect collection (foraging) in Africa has been a female occupation. A study shows that most cricket farmers in Kenya are women (Halloran 2017). In Thailand, about half of the cricket farmers who were interviewed for this report were women. That said, observational evidence carried out for this report shows that black soldier fly farming is a male-dominated field. The country-level survey indicates that 80 percent of the surveyed farmers were identified as "poor" or "lower-middle class." This presents opportunities to expand frontier agriculture among vulnerable populations. Some of these efforts are already taking place. The report uncovered insect farming projects that target refugee populations in Kenya and Uganda and hydroponic projects that target women and youth in Djibouti, Kenya, South Africa, and Sudan. The report's modeling estimates that black soldier fly farming could generate up to 57,000 direct jobs and 160,000 indirect jobs in Zimbabwe alone.

> *A benefit of insect farming is that it's a source of employment and income for both young and old.*
>
> *—Kenyan farmer*

Insect farming can reduce high levels of organic waste, including organic waste from agriculture and other industries. Some farmed insects, most notably BSFL, are capable of consuming most organic waste as substrate feed (Li et al. 2011; St-Hilaire et al. 2007; Tinder et al. 2017; Chen et al. 2019). These substrates include vegetable waste, mixed household waste, and industrial waste from breweries, wineries, or other industries with organic waste. The report's farm-level survey reveals that insect farmers use multiple substrates. Nearly half (43 percent) of the surveyed farmers use household waste as insect substrate. About 64 percent of farms also use industrial food waste, mainly brewery waste, and 12 percent use animal manure. Another 30 percent of farms, mainly cricket farms, use commercial animal feed, such as chicken feed, as substrate. The high diversity of substrates demonstrates the potential of insects to convert all sorts of low-value organic waste streams into protein. This makes the black soldier fly an ideal candidate for breeding in African FCV countries where organic waste management is a challenge, especially in cities. One insect larva can consume between 25 and 500 milligrams of organic matter per day depending on the size of the larvae, the type of substrate available, and the feeding conditions, which include air supply, temperature, and moisture levels (Makkar et al. 2014). The report's modeling projects that BSFL could consume more than 200 million tons of crop waste in Africa.

> *The hatched larvae of the black soldier fly help to break down domestic and industrial waste and contribute to keeping our communities clean and safe for all.*
>
> *—Ghanaian farmer*

Farmers can use the waste from insect farming and hydroponics to replenish the soil. Many parts of Africa have arid or low-fertility soils. Frass, or insect manure, is rich in nitrogen, phosphorus, and potassium (NPK) and can be used as an organic biofertilizer for crop soil, replacing or supplementing chemical fertilizers. A study on Thai cricket farms found that cricket biofertilizer has a higher percentage of NPK than other organic fertilizers (Halloran et al. 2017). Another study found that BSFL biofertilizers increase crop yields (Temple et al. 2013), and this report's research found anecdotal evidence that insect biofertilizer is improving crop growth in Africa. In addition to its benefits for soil, insect biofertilizer also carries a high market value. The report's modeling estimates that the total amount of BSFL frass that could be produced in Zimbabwe would garner between US$1 billion and US$3 billion in fertilizer markets. Hydroponic crop waste could also help revitalize soils as an additional substrate for insects to consume or as an organic compost or green manure for degraded land. The report's modeling projects that BSFL in Africa could produce more than 60 million tons of frass.

> *The mopane caterpillar's manure fertilizes soil. The plants that use it are regenerated.*
>
> —*Congolese farmer*

Frontier agriculture requires fewer natural resources than traditional agriculture and livestock farming. Most critically, these systems require less energy, land, and water and no arable land. Both farmed insects and hydroponic crops can be grown in high densities, and production systems can be set up in small areas and in layers, including indoors and on top of buildings and structures, whereas traditionally crop farming and livestock rearing mostly require large areas of arable land. Moreover, frontier agriculture does not degrade the soil; instead, it can improve the soil health of traditional cropland by applying insect frass as a natural fertilizer. Frontier agriculture requires less water per kilogram of food production and, therefore, does not deplete limited water resources. For example, insect farming for animal feed requires less water than soybean farming to produce a ton of protein. Hydroponic farming requires approximately 80 to 99 percent less water than traditional field-based agriculture (Despommier 2010). Hydroponic systems can even reuse the water when operating a closed system. This separation removes the harm posed to the natural ecosystem from deforestation, monoculture, or any other form of environmental degradation caused by agriculture. It also makes frontier agriculture attractive for food insecure populations that do not have access to land and have limited access to water resources, including people living in cities, arid areas, or refugee camps and settlements (see examples later in this overview).

Frontier agriculture consumes less energy than traditional agriculture and fertilizer production. This report's modeling shows that replacing 6 to 17 percent of the traditional feed production used for Zimbabwean livestock with BSFL meal production reduces energy consumption by 350,000 to 1 million megawatt hours (MWh). Replacing synthetic NPK fertilizer with an equivalent quantity of frass fertilizer reduces energy needs by 600,000 to 1.8 million

MWh. As a result, the modeling estimates that the total energy savings from BSFL meal and frass production in Zimbabwe is between about 1.0 million and 2.8 million MWh. By extending this modeling to Africa as a whole, black soldier fly farming saves between 42 million and 129 million MWh of energy, which would be enough to power between 4 million and 12 million homes in the Northeastern United States. Hydroponic systems can be sustainably powered by renewable energy sources such as solar panels such as solar panels.

Frontier agriculture can mitigate climate change by using waste to feed insects and emitting fewer GHGs than conventional agriculture. Insects produce a high-quality animal protein with up to 20 times fewer GHG emissions than ruminant livestock and up to half the emissions of poultry production per kilogram of edible protein (Halloran et al. 2016; Smetana et al. 2016; Halloran 2017; van Huis and Oonincx 2017; Oonincx and de Boer 2012). A study in Indonesia found that composting kitchen waste with BSFL can reduce $CO_2$ emissions by 47 times and reduce global warming potential by half (Mertenat, Diener, and Zurbrügg 2019). Substituting fishmeal in favor of BSFL meal in animal feed can reduce global warming potential by up to 30 percent (Mertenat, Diener, and Zurbrügg 2019). Another study shows that using BSFL meal instead of soy meal in pig feed reduced global warming potential by 10 percent and required 56 percent less land (van Zanten et al. 2018). This report's modeling shows that feed production for Zimbabwe's livestock population produces approximately 3.4 million tons of $CO_2$-equivalent emissions. The model estimates that BSFL meal production can meet between 6 and 17 percent of total livestock protein demand in Zimbabwe. This would reduce the GHG emissions from traditional feed production by between 190,000 and 570,000 tons of $CO_2$-equivalent. Likewise, replacing synthetic NPK fertilizers with frass fertilizers would reduce emissions from the fertilizer production process by 220,000 to 650,000 tons of $CO_2$-equivalent.[10] As such, the model estimates that the overall reduction in GHG emissions from using BSFL frass and feed is between 400,000 and 1.2 million tons of $CO_2$-equivalent. For comparison, this would be equivalent to removing 90,000 to 265,000 motor vehicles from the roads every year (EPA 2018). By extending these projections to Africa as a whole, using BSFL instead of traditional feed would reduce $CO_2$-equivalent emissions by 86 million tons, the equivalent of removing 18 million motor vehicles from the roads. Hydroponics can also reduce carbon emissions if natural heating is used in greenhouses or renewable energy is used for electricity needs.

## CHALLENGES

The costs associated with high-tech insect farming and hydroponics can be high, but they are much lower, or negligible, in low-tech production systems. In many parts of Asia, Europe, and North America, high-cost systems lead to higher priced products than grains, soil-grown produce, and other animal source proteins. In Africa, however, labor costs are lower than in other parts of the world, which can make insect and hydroponic products more competitive.

This has already started to happen. For example, in Kenya, the price for a ton of BSFL is now lower than the price of a ton of soybeans. Like insect farming, hydroponic farming can also be done using low-tech systems. In high-tech hydroponics, energy and facility construction costs can be high, particularly for all-inclusive modular systems as seen in Korea and South Africa. Some hydroponic operations also require controllers, greenhouses, computer systems, large-scale lighting fixtures, ventilation and heat recovery systems, and specialized labor (Pantanella et al. 2012). However, simpler hydroponic systems can be much cheaper. In West Bank and Gaza, for example, a basic system costs US$820. In Kenya, the pilot hydroponics project in Kakuma Refugee Camp shows that initial investment costs can be recouped after 3.2 years for household hydroponic systems and 2.4 years for group hydroponic systems (WFP 2020).

Currently, several factors constrain the widespread adoption of insect and hydroponic farming in Africa. These factors create barriers to entry that are specific to a farmer's location and access to markets and technologies. Many of these factors are a result of the relative newness of both technologies. In Africa, the foraging and consumption of plants and insects is not new, but insect and hydroponic farming are still nascent industries. For example, according to the surveys, farming crickets has been practiced in Africa for only 20 years. Farming of other insects, such as black solider flies, has been even more recent. This newness means that the industry is still underdeveloped and not well understood by many. This contributes to six main constraints to the widespread adoption of these technologies in Africa:

1. There is a general lack of knowledge and learning systems available. The farm surveys show that African farmers are willing to farm insects but lack knowledge on how to go about it, including knowledge on the production cycle and nutritional gains for humans and animals. The same is true for hydroponics. There are also knowledge gaps for both technologies in technical know-how and market comprehension and few learning or monitoring and evaluation systems.
2. There are a limited number of organizations and institutions to transfer this knowledge. This includes the absence of formal training opportunities and informal peer-to-peer learning through producer groups. However, the survey shows that knowledge and learning increased in areas located near insect research facilities in Ghana and Kenya.
3. Regulatory frameworks on food safety and production methods are weak for the insect farming and hydroponic farming sectors in Africa. This makes it difficult for the industry to develop or for potential farmers to enter the market because there is no clear guidance on production or food safety protocols. Other parts of the world have tried to correct this. For example, in Thailand the government developed a Good Agriculture Practice certification for farmers. Moreover, different insect species require different production processes; therefore, regulations must guide farmers on these

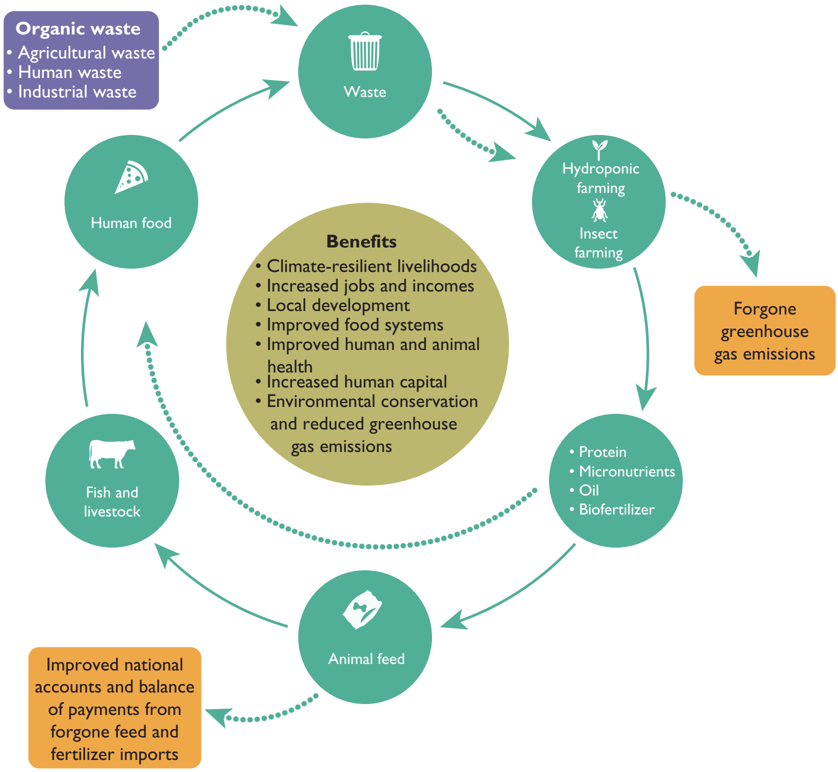
processes to produce insects that can be safely consumed. There are no notable champions among African governments supporting these sectors or guiding potential stakeholders. For example, as of mid-2021, there were no insect or hydroponic sector plans or strategies among African governments. One of the problems is that insect and hydroponic crop farming are still emerging sectors and have not yet caught the attention of many policy makers. Korea's government is one of the few that has developed an Insect Sector Plan. Such a plan could serve as a model for African governments to develop supply chains and manage risks.

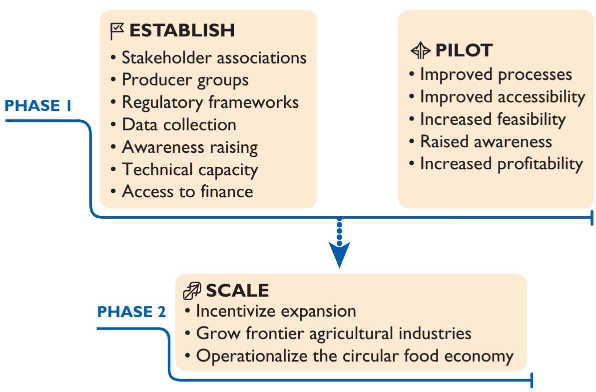
4. Farming subsidies still artificially prop up conventional farming. These subsidies lower the costs of conventional farming at the expense of the environment and frontier agricultural technologies. By contrast, governments in some higher-income countries—such as Denmark, Korea, and the Netherlands—provide funds to kick-start insect farming.
5. There is insufficient access to finance, and there are very real cost constraints for farmers to access inputs or expand operations. Farmer surveys show that many farmers would like to expand their production but are not able to because of a lack of finance. The survey also shows that high start-up costs and limited access to inputs—such as eggs, substrates, or hardware—can set back production. For example, in Madagascar, farmers who were interviewed said they had to travel more than 50 kilometers to buy insect eggs. In Kenya, the research team observed that many of these input and scaling constraints were removed when farmers had greater access to finance.
6. There is still some cultural aversion toward consuming insects, although this seems to be more of an issue in Europe and North America than in Africa. The survey results in Africa showed that most of the interviewed farmers in Africa are comfortable with the idea of eating insects or feeding them to livestock.

## WAYS FORWARD

Figure O.7 demonstrates how frontier agriculture fits within the circular food economy and generates multiple benefits. To summarize, farmed insects can feed on organic waste, including industrial and agricultural waste. This turns a liability of the linear food economy into an asset of the circular food economy, by reducing and reusing society's waste. The figure shows that farmed insects and hydroponic crops are used as sources of protein, micronutrients, oils, and biofertilizer. These nutrient sources are then converted to feed for fish and livestock, which humans consume. Humans can also consume insect and hydroponic products directly. The waste from insect and hydroponic farming is then fed back into the system and used as substrate and fertilizer. All of this generates multiple benefits, including less waste, fewer GHG emissions, more climate-resilient jobs, diversified livelihoods, improved human and animal

**FIGURE O.7 Benefits and Processes of Insect and Hydroponic Farming within a Circular Economy**




*Source:* Original figure for this publication.

health, enhanced local and regional development, and improved food systems and food and nutrition security.

The process of implementing a circular food economy based on frontier agricultural technologies can be organized into two phases. The first phase establishes and pilots frontier agricultural systems, such as insect and hydroponic farming. To establish the necessary foundation of institutions and frameworks to carry the effort forward requires several key actions, such as training farmers; forming producer groups and building producer capacity; providing access to finance; forming entomophagy and hydroponic associations; raising public awareness of the social, economic, and environmental benefits of hydroponic and insect farming agriculture; strengthening regulatory frameworks; and monitoring and evaluating. Piloting frontier agricultural systems would generate learning that could demonstrate their benefits and limit potential inefficiencies. Such pilots would also improve the functionality of frontier agricultural operations and improve the operations' cost-effectiveness. The second phase scales up the frontier agricultural production systems at large enough levels to shift existing linear food economies into circular food economies. This will eventually bring down costs and enhance the competitiveness of insect farming and hydroponic agriculture. It will also reduce waste and protect the environment. Both phases will require action from the private and public sectors, including through public-private partnerships. For example, the public sector could provide extension services, necessary policies, or a regulatory framework, while the private sector could contribute starter capital or other investments. The two phases would address the major factors, listed previously, that constrain the widespread adoption of insect and hydroponic farming in Africa. Figure O.7 shows how these two phases—(1) establishing and piloting and (2) scaling—propel the circular food economy, leading to many direct benefits.

The insect farming project in Kenya's Kakuma refugee camp could serve as a model for other insect production pilots (see box 4.1). The pilot trained refugees in cricket farming techniques. The project started out with a pilot cricket farm and provided training to 15 refugee household heads. Since then, the project has trained more than 80 household heads in rearing and processing farmed insects. These household heads—who have fled from conflict in countries like Burundi, the Democratic Republic of Congo, and South Sudan—are now producing crickets for household consumption and animal feed. DanChurchAid is planning to scale up the initiative by training more farmers and distributing starter kits to more refugee households. The project shows the potential for insect farming to provide livelihoods and incomes for marginalized communities, even in FCV situations.

The hydroponic project in West Bank and Gaza could serve as a model for other hydroponic pilots (see box 5.2).[11] In 2012, the pilot established nutrient film technique and wicking bed production systems to increase local incomes, nutrition, food and nutrition security, women's empowerment, and the competitiveness of the agricultural cooperatives sector. The pilot established 35 nutrient film technique units and 52 wicking bed units with marginalized and underprivileged families in remote areas of the Bethlehem and Hebron governorates. The pilot included education modules at a local technical school to train students in these technologies. The families consumed most of the food that was produced and sold the surplus to local markets. This pilot has since advanced and produces different crops in new systems.

## NOTES

1. The World Bank's Africa Sustainable Development Policy Unit, based on data from the Food and Agriculture Organization of the United Nations.
2. Based on World Food Programme data from January 24, 2021.
3. World Bank Climate Change Knowledge Portal.
4. World Bank Climate Change Knowledge Portal.
5. Office of the World Bank's Chief Economist, Africa Region.
6. The fiscal year 2021 list of FCV countries in the Africa region (not including North Africa): Burkina Faso, Burundi, Cameroon, the Central African Republic, Chad, the Comoros, the Democratic Republic of Congo, the Republic of Congo, Eritrea, The Gambia, Guinea-Bissau, Liberia, Mali, Mozambique, Niger, Nigeria, Somalia, South Sudan, Sudan, and Zimbabwe (http://pubdocs.worldbank.org/en/888211594267968803/FCSList-FY21.pdf).
7. Food and Agriculture Organization of the United Nations, 2018: http://www.fao.org/animal-production/en/.
8. Our World in Data (https://ourworldindata.org/soy).
9. This definition is adapted from that of the Ellen Macarthur Foundation (https://www.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail).
10. Given frass production of 285,545 tons (at 10 percent conversion) to 856,635 tons (at 30 percent conversion).
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World Hunger Education Service. 2018. “Africa Hunger and Poverty Facts.” Hunger Notes, updated August 2018. https://www.worldhunger.org/africa-hunger-poverty-facts-2018/.

Dorte Verner and her team are once again ahead of the curve with this book, bringing solutions to the food security and climate crises. As an entomologist, I see how insect—but also, hydroponic—farming can be unconventional game changers. This book reminds us that there are many solutions that already exist around the world and in Africa, in particular, that if adopted can be scaled.
***—Agnes M. Kalibata, UN Secretary General's Special Envoy and President, Alliance for a Green Revolution in Africa***

This book on frontier agricultural technologies is very timely, and clearly articulates the prospects of insect farming and hydroponic farming technologies to transform traditional agriculture into a new circular food economy. It provides a road map for scaling these technologies in a phased manner through effective public-private partnerships. This is an indispensable reference book for all stakeholders in the emerging areas of commercial edible insect farming and hydroponics.
***—Segenet Kelemu, Director General and CEO, International Centre of Insect Physiology and Ecology***

Innovations in agriculture are needed to improve the food insecurity of the poor. The COVID-19 pandemic is deepening inequalities, and its impact is amplified for marginalized communities, including refugees. UNHCR appreciates our collaboration with the World Bank. We believe that insect and hydroponic farming offer critical innovations. We therefore wholeheartedly endorse this work and applaud such efforts as necessary and important to ending food insecurity.
***—Raouf Mazou, Assistant High Commissioner for Operations, UN High Commissioner for Refugees (UNHCR)***

I am pleased to endorse this important publication which demonstrates how hydroponics allow food and fodder production in settings where traditional agriculture is challenging and new adaptive solutions are required. Several WFP projects in Africa and elsewhere focus on small-scale hydroponics solutions, either to improve diets of families and communities through self-production, or to generate income. This publication affirms the viability of such projects and offers some insight on how these strategies can be taken to scale.
***—Valerie Guarnieri, Assistant Executive Director, UN World Food Programme (WFP)***

Dorte Verner's book on the new circular food economy in Africa brings a fresh perspective on the promise of frontier agriculture at a time when climate change is threatening our food systems. A must-read for anyone interested in tackling food insecurity.
***—Makhtar Diop, Managing Director, International Financial Corporation***

We are increasingly aware that today's food systems are neither sustaining most people nor the planet. Our challenge then is to provide a healthy, affordable diet for everyone, produced sustainably. Frontier agricultural technologies can offer a part of the solution, providing nutritious food in resource-constrained environments. This important book makes a case for piloting these approaches, especially in fragile and conflict-affected countries. We have no time to waste.
***—Rachel Kyte, CMG, Dean, Fletcher School, Tufts University***

A key future challenge is to produce more with less, while improving the livelihoods of small-scale farmers and the ecosystems they depend upon. A promising path forward is to substitute the area-extensive animal feed and biofuel production with a combination of new frontier agriculture as suggested by the authors, with increased use of cultivated land for plant-based food production.
***—Jakob Kronik, Director of International Cooperation, Forests of the World***

The need for innovative ideas and doing things differently has never been greater. I firmly endorse the findings and recommendations of this book. With the launch of the new WFP innovation hub for East Africa in Nairobi, we look forward to working with the World Bank on advancing and scaling up these innovative approaches.
***—Michael Dunford, Regional Director for Eastern Africa, UN World Food Programme (WFP)***

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