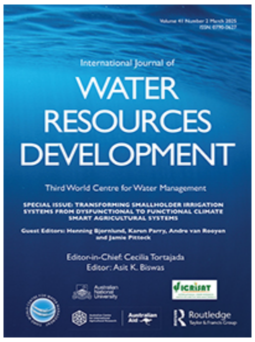

International Journal of Water Resources Development

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/cijw20

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To cite this article: Andre van Rooyen, Henning Bjornlund, Martin Moyo, Jamie Pittock, Karen Parry & Angeline Mujeyi (2025) Agroecology and circular food systems: decoupling natural resource use from rural development in sub-Saharan Africa?, International Journal of Water Resources Development, 41:2, 489-511, DOI: 10.1080/07900627.2024.2449224

To link to this article: https://doi.org/10.1080/07900627.2024.2449224

Published online: 29 Jan 2025.

INTERNATIONAL JOURNAL OF WATER RESOURCES DEVELOPMENT
2025, VOL. 41, NO. 2, 489–511
https://doi.org/10.1080/07900627.2024.2449224

Agroecology and circular food systems: decoupling natural resource use from rural development in sub-Saharan Africa?

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ABSTRACT
This paper proposes transitioning food systems in sub-Saharan Africa to circularity and greater diversity, using agroecology principles and shifting mental models of development from scale to scope. We argue that integrated dryland and irrigated agroecosystems can increase production efficiencies when aligned with local food demands and cultures. Synergies between food enterprises, their products, byproducts and waste will generate further enterprises and tighten resource cycles, closing nutrient, water and energy loops while reducing reliance on external inputs. This will generate more economic benefits per unit of land, labour and water, decoupling local economies from natural resource use and environmental impact.

ARTICLE HISTORY
Received 28 October 2024
Accepted 28 December 2024

KEYWORDS
Agroecology; circular food systems; food systems' transformations; sustainable agriculture; small-scale irrigation

SUSTAINABLE DEVELOPMENT GOAL
SDG 12: Responsible consumption and production

Introduction

Sub-Saharan Africa (SSA) faces critical challenges as the region's population is projected to double from 1.3 billion in 2020 to 2.5 billion by 2050 (Falcon et al., 2022). Feeding an additional 1.2 billion people within the planetary boundaries is a daunting prospect. Food demand will increase along with population growth, and with urbanization and income growth, diets are changing towards more animal-sourced and processed foods (Delgado et al., 2001; Falcon et al., 2022). The question is: Can SSA produce enough nutrition for its growing population by 2050?

Even though cereals alone cannot provide a balanced diet, many studies use cereal supply and demand as high-level calorie proxies for food security based on human energy requirements. Currently, cereal production in SSA falls short of domestic needs, resulting in more than 20% of the demand being imported (FAO Stat 2017 as cited in Kuhn & Britz, 2021). To achieve self-sufficiency by 2050, cereal production must triple (Van Ittersum et al., 2016), which is consistent with Onyutha (2018) who also argues that population increases faster than productivity gains. Moreover, increases in cereal production are significantly linked to the area harvested, suggesting the need for significant

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intensification to reduce food deficits. Some argue that there is sufficient land in Africa to reach self-sufficiency through the extensification of cropland (Kuhn & Britz, 2021); however, this approach could negatively impact biodiversity conservation and diminish rangeland-based livestock production. Further, the cultivation of more marginal land risks increasing land degradation.

African soils are derived from ancient, weathered parent material and are generally poor. They have low fertility (nitrogen (N) and phosphorus) and water-holding capacity and are deficient in micro-nutrients (Kihara et al., 2020; Sanchez, 2002; Van Straaten, 2011). Crop response to fertilizer varies significantly depending on the soil's parent material (Bonilla-Cedrez et al., 2021; Sileshi et al., 2022). In addition, soil acidity compounds low productivity in large areas of SSA (Desta et al., 2021). Hence, the land suitable for agricultural expansion is limited (Chamberlin et al., 2014). Agricultural practices have further degraded the soil due to poor nutrient supply and limited inorganic nitrogen and phosphorus application. Hence, crop production has stagnated or even declined in some places. Considering importation and distribution costs and the challenges to access appropriate fertilizers, Elrys et al. (2020) calculated the N requirements for Africa to feed itself by 2050 and concluded that it was not feasible to increase the N fertilizer rate to the required 181 kg N/ha/y within 30 years. Alternatively, they argue that applying 77 kg N/ha/y inorganic N and 48 kg N/ha/y as organic N is feasible and can achieve the same outcome. Integrating livestock and utilizing N-fixing legumes, such as pigeon peas and groundnuts, and using the right rhizobium inoculants can add up to 300 kg N/ha to the soil in a season (Ibeawuchi, 2007). Phosphorus is the most yield-limiting nutrient, and Magnone et al.'s (2022) calculation of phosphorus application rates suggests that the elemental application rate of phosphorus of 7 kg/ha in 2020 must more than double to 15 kg/ha to ensure food self-sufficiency. Phosphorus can be supplied by recycling on-farm organic material such as composted animal manure (Almeida et al., 2019; Faridullah et al., 2018), highlighting the importance of livestock and animal-sourced foods and of integrating crop and livestock production systems for more efficient nutrient cycling.

Between 1973 and 2013, meat and milk consumption in developing countries increased six-fold and four-fold, respectively (FAO, 2018 as cited in Latino et al., 2020). This trend is expected to continue, with consumption increases in urban areas predicted to be greater than in rural areas. Increased livestock numbers, output per unit, and livestock feed will be required to meet this demand, heightening the risk of environmental impact if not managed properly (Steinfeld et al., 2006). Improved livestock management and its integration with crops are dual imperatives for biomass to be processed into high-value protein, which would then be available for reproductive women to ensure children's cognitive development (Hulett et al., 2014).

Water's role extends beyond food production and plays a prominent and unique role in economic development. As countries develop and populations expand, water demands will increase disproportionately over and above the need for food production. While per capita water use may stabilize or decrease through efficiency and consumer awareness (Eghbali & Sayehmiri, 2022; Falkenmark, 1997) we can expect increased water extraction in the short term as Africa's population and living standards increase. Commensurate with this, there is a growing reliance on irrigation development. However, the question remains whether irrigation can secure adequate food supplies and support adaptation to climate change. Using spatially explicit modelling, Xie et al. (2014) illustrated the significant contribution of small-scale irrigation to increasing food production in SSA. However, they also concluded that a potential increase in irrigated land between 6–14 million hectares and a business-as-usual production scenario would only reduce the demand for total food imports from 54% to 17–40% (depending on the total area developed). While this significantly reduces imports, it is insufficient for food security. Additionally, these calculations neither factored in climate change nor differentiated between areas used for food or non-food crops or whether crops were for local food production or export, which further compromises the ability to improve food security. The calculations also assume that the small-scale irrigation component of irrigation development is socio-ecologically sustainable.

Conventional intensification and industrialization may be insufficient to meet SSA's food production needs by 2050 while staying within planetary boundaries. As noted, increasing food production to reduce imports will require more irrigated land and other resources. Water, nutrients, land, and labour efficiencies will have to improve drastically, while losses, pollution, land degradation, and emissions must be reduced. Therefore, a new paradigm is required in how food is produced, processed, transported, and utilized to reduce food imports and ensure a nutritious diet for Africa's population. In essence, SSA needs to transform its food systems to decouple food production and economic growth from resource use. Decoupling encompasses reducing the use rate of primary resources per unit of economic activity (UNEP, 2011) thus using less energy, water and land resources for the same economic output. Gains in productivity or efficiency of natural resource use are widely recognized as strategies for achieving sustainable economic development, which is desperately needed in rural areas in SSA. Further, decoupling increases economic output while reducing the negative environmental impacts of agriculture, such as land degradation, excessive water extraction, greenhouse gas emissions and other forms of pollution. Such transformations must commence at the production point while stimulating human and economic development. This is particularly true for small-scale irrigation schemes, which must play a role in efficient resource use, including water, and enhancing profitability to improve the local economy in their rural communities.

The Australian Centre for International Agricultural Research (ACIAR)-funded 'Transforming Irrigation in Southern Africa' (TISA) project in Mozambique, Tanzania and Zimbabwe achieved significant success in transitioning small-scale irrigation systems from inefficient (low output and high losses), subsistence-oriented systems to more profitable and efficient irrigation schemes. The transition resulted from socio-technical improvements (soil moisture and nutrient monitoring tools and agricultural innovation platforms) and support and investments from other actors in information services, infrastructure development and market participation (H. Bjornlund et al., 2020). Through water and nutrient monitoring tools, farmers learned they could reduce irrigation intensity and retain nutrients in the root zone effectively, leading to increased crop yields, water productivity, levels of farmer participation and investment in infrastructure maintenance (Mdemu et al., 2020, 2023; Moyo et al., 2020; Pittock et al., 2020; Van Rooyen et al., 2020). This reduced water-related conflicts and led to greater self-organization (Mdemu et al., 2023; Moyo et al., 2020). Remotely sensed data by Wellington et al. (2023) revealed a decoupling of gross primary production from evapotranspiration on some irrigation schemes. This significant finding and achievement raised the question about the potential for decoupling further productivity and economic gains from natural resources and decoupling local economic development from environmental impacts. In pursuit of this, a follow-on project explores strategies towards greater efficiency and systems transformation. Additionally, TISA's findings highlight the potential for functional small-scale irrigation systems to serve as central hubs of circular food systems, supplying products to micro, small and medium enterprises for processing into value-added products. This is congruent with the literature that provides evidence that a circular bioeconomy can decouple development from natural resource use and impact (Lever & Sonnino, 2022; Scheel et al., 2020). Thus, the potential of small-scale irrigation systems to improve resource use efficiency, including water use, and both supply and receive inputs from other local farm and non-farm enterprises makes a compelling rationale to study these schemes as case studies of stimulating and contributing to circularity.

A growing body of literature recognizes agroecology as a framework for transforming food systems. Agroecology offers a systems approach to sustainable food production and consumption that can also decouple development from natural resource use and impact (Betancourt, 2020). By prioritizing soil health, biodiversity and ecosystem services, agroecology aligns with and promotes circular economy principles in agriculture, reducing waste and environmental degradation (Bezner Kerr et al., 2021; Gliessman, 2018; Gliessman, 2020; Sijpestijn et al., 2022; Wezel et al., 2009, 2020). Some argue that the adoption of agroecological principles in circular food systems approaches is essential for ensuring food security, improving nutrition and mitigating climate change (Ditlev-Simonsen, 2022; Zhang et al., 2022). A new paradigm focusing on more multidisciplinary and systems-based research and development strategies to increase nutritious food production within the planetary boundaries is urgently needed. These strategies will shift the current focus from producing more calories to producing more nutritious food and managing and improving infertile and degraded soils with minimal use of inorganic fertilizer.

This paper explores the role of agroecology in circular food system transformations in the context of functional small-scale irrigation schemes and associated dryland farming communities, and our intent to use these communities as learning sites about transitioning to circularity. The rationale for focusing on the communities around these schemes coalesces around the need to improve food security, crop and livestock integration, resource use efficiency and rural economic development. These schemes have a measure of integration with respect to the ecological landscape and governance units under which they are administered. Further, all irrigators also own dryland plots (but not all dryland farmers have irrigated plots) and irrigators are organized into groups with strong internal networks that reach dryland farmers. These existing networks provide a platform for integrating farming activities to strengthen circularity.

The paper examines the potential of agroecological practices to facilitate a paradigm shift, guiding food systems' transformation from linear and unsustainable practices to being circular, regenerative and decoupled from natural resource use and environmental impact while also stimulating sustainable economic development through linked micro, small and medium enterprises (MSMEs). This is especially critical as cropping expands into marginal land. The rest of the paper is structured as follows. The next two sections introduce circular food systems and agroecology as a theoretical framework for system transformation that addresses five levels of food systems change. Then, there is a section on local enterprises and how MSMEs can link producers with consumers, and a consideration of natural resource flows between farm and non-farm businesses as a possible basis for business models. The next section introduces the concept of economies of scope and integration as alternative rural development strategies to economies of scale. This is followed by a section that explains our proposition to use small-scale irrigation schemes as learning sites to foster and strengthen circularity. The following section brings the concepts together, showing how the agroecological framework and consideration of appropriate scale can be applied to developing communal irrigation as hubs for circular food systems. The paper concludes with a discussion of the main takeaways and overall conclusions.

Circular food systems

A circular economy aims to increase sustainability by reducing resource consumption and the negative impacts of environmental discharges (Hamam et al., 2021; Kirchherr et al., 2017; Schroeder et al., 2019). It involves sharing, repairing, renovating, and recycling or reusing materials and products for as long as possible, reducing waste and providing a more sustainable alternative to the current linear model of 'take, do, and dispose of'.

The circular bioeconomy is a specific component of the circular economy that focuses on an economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources from land and sea – such as crops, forests, fish, animals and micro-organisms – to produce food, materials and energy. To minimize environmental impact, the goal is to convert waste from biological sources into valuable products like biofuels, bioplastics and organic fertilizers. This approach often involves leveraging technological advancements to maximize biomass conversion into high-value products, with a strong emphasis on the role of biorefineries and advanced waste management methods (for in-depth reviews and definitions see Giampietro, 2019; Tan & Lamers, 2021).

Based on this, a circular food systems approach aims to transition linear food production systems (production, processing, consumption and waste discard) to circular systems. Authors focusing specifically on circular agricultural production systems define them as:

> the set of activities designed to not only ensure economic, environmental and social sustainability in agriculture through practices that pursue the efficient and effective use of resources in all phases of the value chain but also guarantee the regeneration of and biodiversity in agroecosystems and the surrounding ecosystems. (Velasco-Muñoz et al., 2021, p. 4)

From this, it follows that circular food systems should search for practices and technologies that minimize the input of finite resources, encourage the use of renewable ones, prevent the leakage of natural resources from the food system (e.g., carbon, nitrogen, phosphorus, water) and stimulate the reuse and recycling of inevitable resource losses in a way that adds the highest possible value to the food system (Jurgilevich et al., 2016). Much of the existing literature focuses on reducing losses of water, nutrients, carbon and energy along food supply chains, including the reuse of food, the utilization of by-products and nutrient recycling, as well as reducing the carbon footprint of agri-food chains. Transitioning existing food systems towards circularity requires careful water, carbon and nutrient management to minimize environmental losses and retain these resources within the system for as long as possible. This involves reusing products and their by-products to increase efficiencies and reduce negative externalities, as per the following examples.

Water cannot be replaced or substituted by anything natural or unnatural. Its increasing scarcity for human and ecosystem use makes it a crucial consideration in designing and monitoring transitions towards circularity. Increased industrialization disrupted the natural hydrological cycle. In linear systems, water quality becomes increasingly degraded until it is no longer fit for use by humans and ecosystems (Nika et al., 2020). Achieving sustainable food production requires improvements in water use efficiencies, recycling, reuse and pollution reduction.

Reducing nutrient losses (i.e., reducing pollution of land, air and water) through tighter nutrient cycles and relying less on nutrient imports is important. Particularly through efficient fertilizer use and reusing 'waste' as by-products for livestock feeds and soil supplements. For the importance of nutrient circularity, see Harder et al., (2021) and Morais et al. (2021).

Edible and non-edible biomass losses contain nutrients, possible pollutants and significant amounts of carbon, leading to unproductive and harmful losses on the biosphere. These losses must be minimized (see Muscat et al. (2021) for an overview). Livestock, especially ruminants, can convert biomass humans cannot digest into highly nutritious foods (Van Zanten et al., 2019) and hence are essential for efficient nutrient recycling. Effective use of energy, human labour, fossil fuels and sunlight is required, thus increasing the output of products per unit of energy used (see Venkata Mohan et al. (2016) for a review of waste biorefinery models for a circular bioeconomy).

There are several more specific approaches to managing circular food systems (Velasco-Muñoz et al., 2021) including:

- *narrowing resource loops* involves the use of eco-efficient solutions that reduce resource intensity and the environmental impacts per unit of product or service;
- *slowing resource loops* involves pro-longing and intensifying the use of products to retain their value over time;
- *closing resource loops* involves creating new value through the reuse and recycling of used materials and by-products; and
- *regenerating resource flows* involves actions to preserve and enhance natural capital.

These management approaches are critical to increasing resource use efficiencies, maintaining resources within the system and conserving and regenerating renewable resources. They form the foundation of circularity and resonate with agroecology. This paper aims to leverage these complementarities in developing circular food systems, drawing on the more explicit pathway to transformation offered by agroecology's principles.

Agroecology

Agroecology is a science, practice and movement to transform food systems (Gliessman, 2016, 2018, 2020; Wezel et al., 2009, 2020). IPES-Food defines agroecology as applying ecological concepts and principles to optimize interactions between plants, animals, humans and the environment while considering the social aspects that must be addressed for a sustainable and fair food system:

> Agroecology is the application of the science of ecology [. . .] to the study, design, and management of sustainable food systems, the integration of the diverse knowledge systems generated by food system practitioners, and the involvement of the social movements that are promoting the transition to fair, just, and sovereign food systems. Within a justice and rights framework, it seeks to minimise external inputs and optimise sustainable interactions between plants, animals, humans, and the broader environment. (IPES-Food, 2018, p. 12)

The foundation of agroecology rests on 13 core principles developed by the High-Level Panel of Experts (HLPE) for Sustainable Food and Agriculture Systems (HLPE, 2019; Table 1). Further, Gliessman (2016) arranged these core principles into five levels of food system change; the first three are actions that farmers can take to convert from industrial or conventional systems to regenerative or environmentally friendly systems; the next two levels go beyond the production system and focus on the broader food system and the societies in which they are embedded:

Level 1: Increase the efficiency of industrial and conventional practices to reduce the use and consumption of costly, scarce, or environmentally damaging inputs.

Level 2: Substitute industrial/conventional inputs and practices by alternative practices.

Level 3: Redesign the agroecosystem to function based on a new set of ecological processes.

Level 4: Re-establish a more direct connection between those who grow our food and those who process or consume it.

Table 1. Agroecology, a framework to transform food systems drawing on the systems, levels, aims, principles, elements and scale of application of agroecology.

System	The 5 levels	Aims	The 13 principles	The 10 elements	Scale[a]
Agroecosystem	Level 1: Increase the efficiency of industrial inputs	Improve resource efficiencies	Input reduction	Efficiency	FA, FO
	Level 2: Substitute alternate practices		Recycling	Recycling	FI, FA
			Soil health	Synergies	FI
			Animal health	Diversity	FI, FA
	Level 3: Redesign whole agroecosystems	Strengthen resilience	Synergy	Resilience	FI, FA
			Biodiversity		FI, FA
			Economic diversification		FA, FO
Food system	Level 4: Re-establish connections between growers and consumers, develop alternate food networks	Secure social equity	Co-creation of knowledge	Co-creations and sharing or knowledge	FA, FO
					FA, FO
			Social values and diets	Culture and food traditions	FA, FO
			Connectivity	Circular and solidarity economy	
	Level 5: Rebuild the food system		Fairness	Human and social values	FA, FO
			Land and Nat Res governance		FA, FO
				Responsible governance	FO
			Participation		

Notes: [a]Scale of application: FI = field; FA = farm, agroecosystem; FO = Food system. Sources: FAO (2018); Gliessman (2016); HLPE (2019).

Level 5: Rebuild the food system. Building on the foundation created by the sustainable farm-scale agroecosystems achieved at level 3 and the new relationships of sustainability of level 4, build a new global food system based on equity, participation, democracy and justice that is not only sustainable but also helps restore and protect Earth's life support systems upon which we all depend (Gliessman, 2016).

The UN Food Systems Summit called for global food systems transformation, and agroecology provides a scientifically accepted framework (Kass, 1996). Moreover, agroecology offers promising pathways towards circular food systems, as many of its core principles will also contribute to circularizing food systems. The main elements in the agroecosystem (levels 1, 2 and 3) include efficiency, recycling, diversity and resilience, which are crucial in any transition towards circular production systems, this paper also proposes to co-design circularity into levels 3, 4 and 5.

We combined Gliessman's levels, HLPE's aims and principles, FAO's elements and HLPE's application scale to provide a framework for transforming food systems (Table 1). The later section on communal irrigation systems provides examples of how this framework can be applied and operationalized in transforming food systems associated with small-scale irrigation schemes.

Food systems transformations based on local enterprises

Transitioning from linear food systems to circularity will require new business models (Donner & de Vries, 2021; Hamam et al., 2021; Salvador et al., 2021). We propose that the primary driver to help transition food systems towards circularity is redesigning existing enterprises (level 3) and stimulating the development of new, interconnected business networks of profitable enterprises (level 4) within the agroecosystem and the food system. These tight interconnected business networks involve local enterprises buying locally produced products and by-products from one another, adding value through primary and secondary processing, serving local markets first and selling excess to markets further afield. This introduces a new and more complex level of logistics and business networks to reduce waste, transport costs and the loss of valuable resources to urban areas.

Chesbrough (2010) viewed business models as a mediating construct between technology and economic value. We suggest using circular food business models to mediate between the environment, technology, economic value and human well-being. Following this, our business model for circular food systems, within agricultural production systems, centres on small-scale irrigation schemes providing an economic and operational architecture and defining the organizational boundaries of different actors. The scope will be determined by: the type of resources available, used and shared; cooperation, trust and the knowledge flows to facilitate circularity; and governance-enabled formal and informal mechanisms (Zucchella & Previtali, 2019).

Maintaining agricultural products and their by-products within the local area will require efficient use of by-products in related enterprises and recycling final waste into the production system. However, circularity will never be complete, and specific imports and exports will be required to fulfil nutrient requirements and revenue inflows as shown in Figure 1. These systems are inherently complex and context specific and we acknowledge that Figure 1 reflects a simplified depiction of the relationships. Circular business model innovations are inherently networked: necessitating collaboration, communication

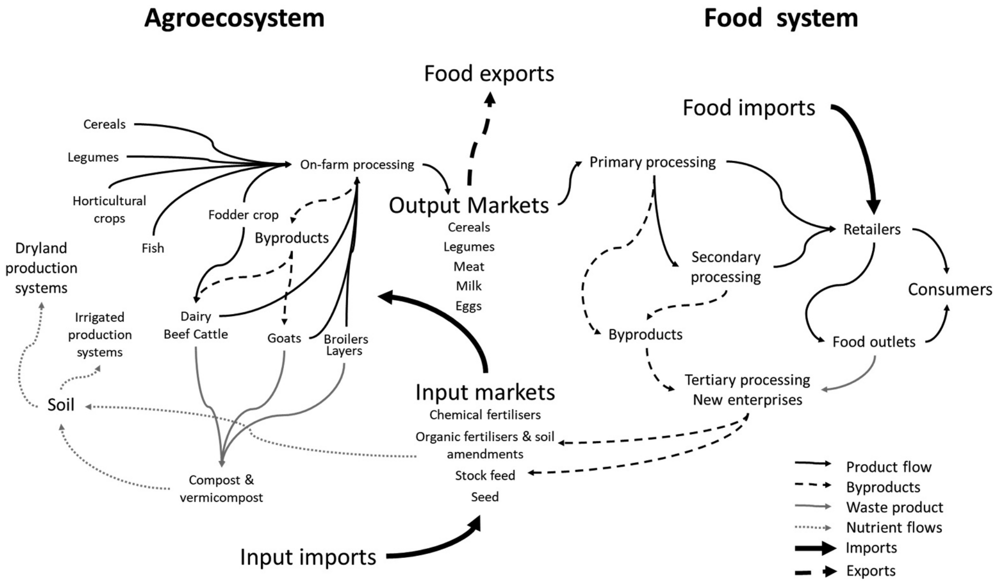

Figure 1. Intentional circularity and relationships within and between production systems in agroecological systems and the product flows in food systems. (First author's vision.)

and coordination within intricate networks of interdependent yet independent actors/stakeholders (Donner & de Vries, 2021). This may require a network orchestrator or an innovation platform facilitator to connect, redesign and co-create actor constellations and how they do business (Zucchella & Previtali, 2019). In our use of innovation platforms in TISA (Van Rooyen et al., 2017), the facilitator supported the development of a shared vision and built trust at the scheme level, whereas, in the case of circularity, the facilitation will also focus on how resources could be used, how by-products could be reallocated to the next level of users at the community level, and development of business models to implement and identify entrepreneurs for training. To ensure that individual businesses function well and that a constellation of enterprises integrate, 'innovative circular business models should be approached by complementing an individual level of analysis with an organisational and network one' (Zucchella & Previtali, 2019, p. 282).

The experience gained by TISA researchers in diverse multi-stakeholder platforms will be essential in structuring and guiding co-development and niche innovations in circular food systems around irrigation schemes. Many of these concepts are represented in Figure 2 (multi-stakeholder platforms), which suggests that reconfiguring existing actors, attracting new actors and innovating various circular business models at the level of the actor network may result in integrated mutually supportive enterprises that reduce losses and increase overall efficiency and economic viability.

Alternative agricultural development strategies

Current conventional, corporate or industrial development strategies are predominately influenced by an 'economies of scale' paradigm. Early factories discovered that leveraging bulk purchasing of raw materials and spreading the fixed costs of expensive machinery over

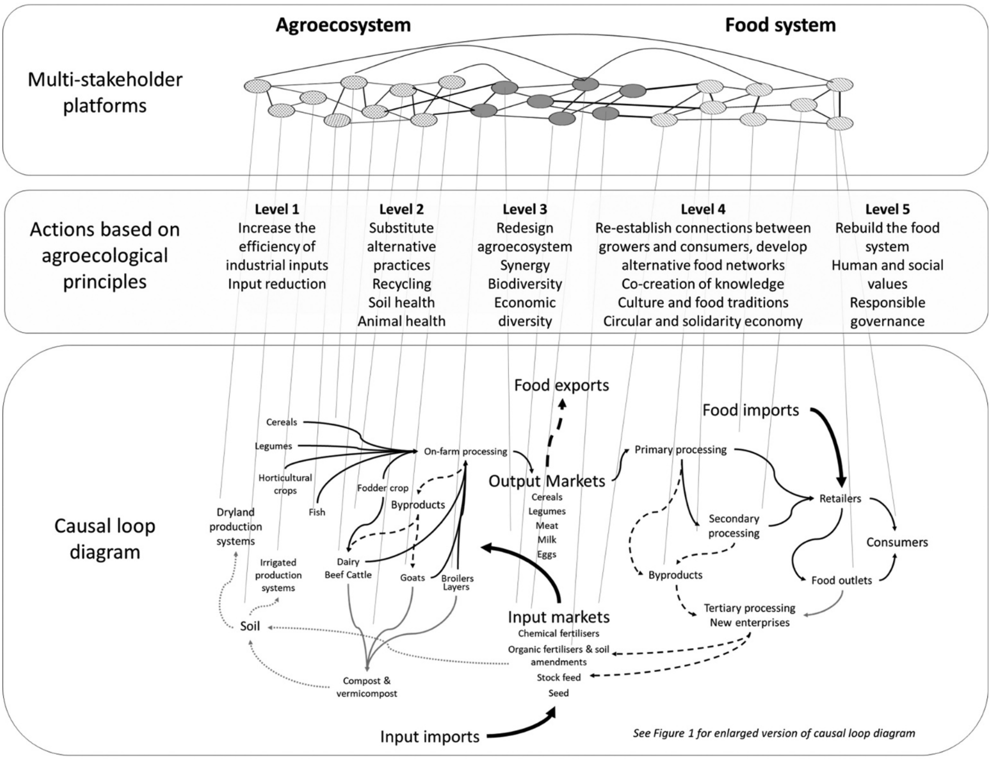

Figure 2. A diagrammatic representation of how multi-stakeholder platforms can be used to tighten networks of stakeholders from the agroecosystem and the food systems for greater information flow and cooperation (upper area) to develop shared visions of circular food systems and then to co-design linked production and food systems based on the principles of agroecology (middle area) and integrate activities, share resources to tighten nutrient cycles, increase the diversity of value-added products resulting in locally viable circular food systems (bottom area). (Authors' vision based on the work of McGlashan et al., 2019, and Wang et al., 2013).

a more extensive production run could lead to significant cost savings per item produced. Economies of scale have increasingly become the central driving force in the corporatization process of modern agricultural production systems. We argue that this paradigm has derailed many sustainable alternatives, forcing African rural development along ill-fitting and unsustainable development trajectories. This caused significant barriers to developing or reverting to more suitable, locally adapted natural resource management strategies guided by the four management strategies towards circular food systems discussed earlier (narrowing, slowing and closing resource loops, and regenerating resource flows).

Many are unaware of alternative, more appropriate strategies, particularly in contexts where development is associated with smallholder farming systems. Hayashi (2011) proposed a new framework for assessing rural development performance based on a three-by-three matrix of the pillars of sustainability – economy, ecology and sociology – and tabulated against three types of improvement strategies: scale (expansion of the production of a single product), scope (introduction of different products) and integration (internalization of the material cycles; Table 2). A framework to evaluate performance can,

Table 2. A framework for assessing and designing rural development strategies based on economic, ecological and social returns on investments in scale, scope and integrations.

Pillars of sustainability	Improvement strategies		
	Scale	Scope	Integration
Ecology	Ecology of scale *Agroecosystem*: Farming units are too small to function at large scale. Ecological scale at production, can only be achieved through aggregation across production units. *Food system*: Local supply and demand are too small to develop large processing and manufacturing plants.	Ecology of scope *Agroecosystem*: Farming units can increase diversity by exploiting different trophic levels in crop and livestock production. Increasing the range of products per unit area. *Food system*: Supply and local processing must diversify to fulfil the range of foods locally demanded	Ecology of integration *Agroecosystem*: Integration of diverse production systems generates synergies based on complementarity. *Food system*: Food processing can integrate to form its own ecology where by-products are shared as input for the next MSME, and waste products re-enter the production system.
Economy	Economy of scale *Agroecosystem*: Small production units cannot function on a large economy of scale. *Food system*: Low supply and demand levels prevent large processing plants that function on large economies of scale.	Economy of scope: *Agroecosystem*: Farming units can increase incomes from a diversity of products. Increasing the total income per unit area. *Food system*: MSMEs can generate income from selling a range of products, rather than selling large quantities of a narrow range of products.	Economy of integration *Agroecosystem*: Income from diverse and integrated production systems is higher than from systems that are not integrated. *Food system*: Production costs of integrated MSMEs, where by-products are locally available from other systems, will be more economical than isolated production systems.
Sociology	Sociology of scale *Agroecosystem*: Large numbers of small-scale producers have significant capacity, agency and strong networks/connectedness. *Food system*: A relatively large consumer base demands significant and diverse food products, that can be processed and produced by a wide range of MSMEs and associated entrepreneurs.	Sociology of scope *Agroecosystem*: Small scale farmers have diverse aspirations, skills, networks. *Food system*: A diverse range of small-scale entrepreneurs have diverse aspirations, skills, networks.	Sociology of integration *Agroecosystem*: Integrating and developing the synergies between the complementary skill sets, networks and aspirations of a strong resilient network of producers can produce a wide range of products and services. *Food system*: Integrating and developing the synergies between the complementary skill sets, networks and aspirations produces a strong resilient network of entrepreneurs that can produce a wide range of foods and related services.

Source: Based on Hayashi (2011).

ergo, be used to help design development programmes. Of the nine possible concepts derived from the matrix in Table 2, certain combinations may be dominant for a business or broader development context. The challenge lies in identifying appropriate combinations. Further, integration occurs within economies, ecologies and sociology, so there must be opportunities for integrating scale and scope.

In large-scale or commercial agriculture, economic returns are primarily based on scale rather than scope and integration. Maize-soya rotations are the closest large commercial farms to get economic returns on both scope and scale. However, from an agroecological perspective, this still amounts to mono-cropping (Grabau & Chen, 2016). While there are emerging signs of change, small-scale agriculture cannot achieve the same economies of scale as large-scale operations, even where attempts are made to merge them into larger cooperatives or contract farming arrangements. However, this has local socio-economic and environmental consequences, as the transport of raw and semi-processed products to cities for aggregation and further processing deprives rural areas of economic opportunities and valuable by-products and doubles the food miles of products that return to rural areas. Processing in cities transfers profit, jobs and business opportunities to middlemen, transporters, aggregators and processors, contributing to the lack of rural economic opportunities and driving urbanization (V. Bjornlund & Bjornlund, 2024).

Similarly, unless farms are coalesced into a larger ecological scale, small-scale producers suffer from the lack of returns on the ecology of scale. In such cases, the only options are returns on the economy and ecology of scope and integration. However, African agriculture functions best when based on the ecology of scope and integration, as small farms are often diversified (scope) and integrated (complimentary instead of merely coexisting enterprises), thus exploiting an economy of scope based on the economy of integration. Diversification of production enterprises, including cereals, legumes and livestock, allows for the utilization and integration at different trophic levels; grains from cereals and legumes are utilized as food and the residues for secondary production (livestock); livestock can also consume the by-products of the primary production system; nitrogen from legumes nourishes soil and livestock; while manure from livestock enriches soil and maintains soil organic matter, which is a critical component in maintaining soil health and water retention. The returns per unit of land and labour invested in diverse and integrated systems are higher than in less diverse systems where the enterprises are not integrated. While high-input, high-output production systems function on the economy of scale, the ecology and economy of scope and its integration (legumes fixing nitrogen, cover crops providing biomass, manure fertilizing crops and crop residues feeding livestock) can also reduce the per unit costs of outputs.

Where African rural areas lack opportunities in the ecology and economy of scale, they provide significant opportunities in the sociology of scale and have significant potential for scope and integration. In our context, small-scale irrigation systems and bordering dryland production systems represent areas with high population densities and diverse social and economic activities encompassing both production and consumption. These farming systems can be leveraged as sources of raw materials for food production and processing, which is primarily for local consumption and with some export out of the community as value-added products. The combination of development concepts suited to this context includes economy of scope, ecology of scope and integration, and sociology of scale, scope and integration. However, this combination will not suit all contexts, and we encourage readers to consider the range of alternative rural development strategies in their specific circumstances.

Our proposition

We propose using agroecology (primarily as a science and practice) to transform food systems to circularity (at the point of production and the rest of the value chain). Therefore, we propose a structured, testable strategy to co-design and facilitate food systems transformation that will decouple it from resource use and environmental degradation. Using the 13 principles of agroecology, we suggest that transitions can be codesigned by agricultural innovation platforms (focusing on the agroecosystem and levels 1–3) and integrated using similar multi-stakeholder platforms with local business players in the food and ancillary businesses (focusing on the food system and levels 4 and 5; Figure 2).

Communal irrigation systems as hubs for circular food systems

Communal irrigation schemes and surrounding dryland production areas are particularly suited to exploration as learning sites for redesigning agroecosystems and food systems towards circularity because they function in the same socio-ecological landscape and resource systems. They are an integral part of the same economic hub (town, growth point, etc.) where they acquire inputs and information and where their most immediate consumers reside. In addition, they are generally governed within the same governance units by the same local authorities and decision-makers. Many irrigators are also involved in dryland farming operations, involving diverse crop varieties and livestock. Production systems are also relatively well integrated within individual dryland farms, between farms and plot owners on the schemes, and between dryland and irrigation farmers. Based on the success of TISA, we argue that once functional and profitable, communal irrigation systems in SSA hold the potential to become hubs for circular food systems. The qualities of these systems – including traditional knowledge, social cohesion and a remarkable capacity for self-organization – can be combined with modernized infrastructure and a focus on resource conservation and contribute to a more sustainable and water-secure future for African agriculture. Functioning irrigation schemes have well-established local institutions and communication and information networks that are conducive to collective action, decision-making and social learning. In the context of agricultural innovation platforms, the existing networks between and among irrigators and dryland farmers form a good base for the co-design of solutions to barriers to transition to circularity.

Most agricultural products from the schemes are currently aggregated and sold to markets in larger business centres and, as reflected earlier, the system could be transformed to stimulate local entrepreneurial and employment opportunities. These schemes are vibrant communities with significant agency and capacity, especially women and youth who are innovative and eager for economic opportunities within the local area. Engaging existing and new entrepreneurs in a network of closely linked MSMEs in the local agricultural processing and food sector can contribute significantly to transforming local food systems and stimulating local economies.

Following the framework in Table 1, we propose a co-design process using a multi-stakeholder approach to redesign the *Agroecosystem* (level 3) and rebuild the *Food System* (level 5). This can be done by reconnecting producers and consumers (level 4) based on the potential diversity of products that farmers can produce in the local agroecology and the needs and requirements of the local food networks and social values, cultures, traditions and diets. These multi-stakeholder platforms can work through the 13 principles to identify opportunities and address challenges to increase efficiency and, where possible, decouple systems. Table 3 provides examples and opportunities to operationalize this process.

Table 3. Application of the food systems transformation framework (Table 1) to small-scale irrigation schemes and associated surrounding communities.

Agroecosystems: The production systems of dryland areas and irrigated plots (field and farm scale)		
Principle	Objective	Examples of operationalizing the process
Level 1: Increase the efficiency of industrial inputs		
1. Input reduction	Preferential use of local renewable resources and close resource cycles of nutrients and biomass as far as possible	Improved water and nutrient monitoring and management enable the reduction in chemical fertilizer input without compromising yields in irrigated fields. In dryland fields, reduced use of chemical fertilizers can be achieved through micro-dosing, a technology pioneered by ICRISAT
Level 2: Substitute alternate practices		
2. Recycling	Reduce or eliminate dependency on purchased inputs and increase self-sufficiency.	Crop residues and their by-products from processing can be combined with resources from rangelands (legume seed and native grasses) to produce nutritious livestock feed. Manure can be recycled using compost and vermicompost to improve soil health.
3. Soil Health	Secure and enhance soil health and functioning for improved plant growth, particularly by managing organic matter and enhancing soil biological activity.	Minimize tillage, maintain roots in the fields throughout the year, and perform intercropping and crop rotation and other regenerating practices. Increase the use of manure and vermicompost to increase soil organic matter and soil health. Using cattle kraaled (penned) at night on fields during the dry season improves soil nutrients and organic matter, ultimately improving soil micro-biological diversity. This will also reduce the reliance on chemical fertilizers and pesticides.
4. Animal Health	Ensure animal health and welfare.	Increased livestock integration will also improve animal health, reproduction rate and the quality and volume of meat produced, increasing farmers' income.
Level 3: Redesign whole agroecosystems		
5. Biodiversity:	Maintain and enhance the diversity of species, functional diversity and genetic resources, thereby maintaining overall agroecosystem biodiversity in time and space at field, farm and landscape scales.	Increase the diversity of crops (cereals, legumes, horticultural crops and trees), diversity in rangelands and livestock (small and large ruminants, poultry) produced (see section on the Ecology of Scope). Consider agroecosystems as embedded in larger natural ecosystems to ensure the sustainability of ecosystem goods and services.
6. Synergy	Enhance positive ecological interaction, synergy, integration and complementarity among the elements of agroecosystems (animals, crops, trees, soil and water).	Improve the integration of biodiverse soil for higher moisture retention and healthier crops. Greater integration between primary and secondary producers for synergies between cereals and legumes, and between legumes and symbionts. (See section on the Ecology of Integration.)
7. Economic diversification:	Diversify on-farm incomes by ensuring that small-scale farmers have greater financial independence and value-addition opportunities while enabling them to respond to consumer demand.	Greater on-farm diversity (scope) and integration result in more market opportunities. A wider range of crops and products produced on-farm will require more diverse markets and offer more processing and value-addition opportunities. (See the sections on the Economy of Scope and the Economy of Integration.)
Food systems		
Level 4: Re-establish connections between growers and consumers, develop alternate food networks		
8. Co-creation of knowledge	Enhance co-creation and horizontal sharing of knowledge, including local and scientific innovation, especially through farmer-to-farmer exchange	TISA introduced Agricultural Innovation Platforms to bring diverse stakeholder groups together to solve challenges and improve system efficiencies at the irrigation scheme level. Similar processes can be used with a wider range of stakeholders to analyse barriers, innovate and co-design new constellations of actors in the micro, small and medium food-related enterprises – linking farmers to local entrepreneurs and reconfiguring networks and linkages to redirect resource flows into circular patterns.

(*Continued*)

Table 3. (Continued).

Agroecosystems: The production systems of dryland areas and irrigated plots (field and farm scale)		
Principle	Objective	Examples of operationalizing the process
9. Social Values and diets:	Build food systems based on the culture, identity, tradition and social and gender equity of local communities that provide healthy, diversified, seasonally and culturally appropriate diets.	As a part of, but also an outcome of, the co-design process described with its increased reliance on scope and integration, we anticipate the production of a more diverse diet of preferred nutritional foods. Rebuilding culturally appropriate, diverse and nutritious food systems.
10. Connectivity	Promote fair and short distribution networks and re-embed food systems into local economies to ensure proximity and confidence between producers and consumers.	The objective is to re-establish the links between dryland and irrigated producers and consumers through local processors. The critical point is to keep food miles as low as possible and export as much processed food as possible to retain by-products within the production areas and increase income by only exporting value-added food from local communities.
Level 5: Rebuild the food system		
11. Fairness	Support dignified and robust livelihoods for all actors engaged in food systems, especially small-scale food producers, based on fair trade, fair employment and fair treatment of intellectual property rights	Developing better food systems will require that all players get a fair deal. Farmers need to get fair prices and value-adding processors need to provide consumers with nutritious food at a fair price. Moreover, consumers need to know that they are treated fairly by offering nutritious food without contaminants produced within the planetary boundaries and, where possible, while regenerating the environment and creating more diverse livelihood strategies. This food system also must offer fair job and business opportunities. All must be able to live dignified lives.
12. Land and natural resource (NR) governance	Strengthen institutional arrangements to better recognize and support (or increase the recognition and agency of) family farmers, smallholders and peasant food producers as sustainable managers of natural and genetic resources	Access to natural resources and land tenure remains a contested issue in Africa. Food systems transformation may be an unconventional leverage point to foster improved NR governance and land tenure. However, linking society with producers through their food may be a viable strategy to bring about greater cohesion, understanding and care for NR and land, especially if food is rooted in local culture, visibly contributing to the rural economy and reclaiming its central societal position.
13. Participation.	Encourage social organization and greater participation in decision-making by food producers and consumers to support decentralized governance and local adaptive management of agricultural and food systems.	Society must be involved in changing food systems. No one component or subsector can change the entire food system – producers must produce better agricultural products, MSMEs must process and make them available as healthy food products and most importantly, consumers must want or even demand nutritious, culturally appropriate food.

Discussion

SSA needs to increase food production significantly to feed its population by 2050 without increasing food imports, but (as argued in the introduction) this is highly unlikely following conventional agricultural practices. Irrigated agriculture can significantly contribute to SSA's food supply (Xie et al., 2018, 2014) but it would still fall short of self-sufficiency. However, most African schemes are not functioning at or even near their potential (V. Bjornlund et al., 2020). The TISA project illustrated that irrigation schemes can be transformed into functional systems by: increasing water productivity through increasing yields with less water and having much more efficient nutrient management; improving access to markets, which resulted in increased incomes and expenditure on food, education and construction; and reinvestment into agricultural production (Mdemu et al., 2017; Moyo et al., 2020). However, it will require significant investment beyond irrigation schemes to increase the nutritious food supply and keep within the planetary boundaries. This paper proposes a systems approach based on proven frameworks to facilitate inclusive food system transformation, linking dryland farmers and irrigators with local entrepreneurs using agroecological principles to guide the co-design of circular food systems (Figure 2). The premise is to increase agroecological efficiencies of production systems through diversification and integration, tightening resource cycles, reducing post-harvest losses, recycling by-products to facilitate synergies in existing and new enterprises, and to cycle final waste products back into local soils using improved composting technologies; thereby, reducing the need for external inputs. The immediate goal is to increase agroecological efficiency to reduce external inputs and reliance on food imports to transition to culturally relevant food systems and achieve relative decoupling. Building on the principles and independent evidence provided by Wellington et al. (2023), the ultimate goal is to decouple local economic growth from natural resource use and environmental degradation by developing circular food systems.

Agroecology recognizes agroecosystems and food systems as distinct sub-systems driven by differing aims and principles but overlapping scales and, in this case, resources. Agroecology promotes circularity in the agroecosystem but not explicitly in the food system (see Table 1). Here, we propose integrating the two systems by; (i) tightening the resource flow loops between the agroecosystem and the food system and (ii) linking growers and consumers to communicate their needs and opportunities to develop or re-establish previously disrupted culturally significant food traditions and linkages (V. Bjornlund et al., 2022). This will require interactions between producers, processors, retailers, outlets and consumers to co-design new agroecosystems and local food systems based on local demand and production potential. Highly inclusive multi-stakeholder platforms are ideal for facilitating these processes (Van Rooyen et al., 2020, 2017).

While agroecology is a sound framework, practitioners' mental models are often based on economies of scale. Considering the ecological, economic and social returns on investments in scale, scope and integration is an appropriate concept to adjust mental models of how integrated and economically diverse systems can emerge from small production units delivering a range of products that are in local demand (De Roest et al., 2018). Small-scale production systems (ecologies) and processing systems (economies), providing returns on scope and integration, are sound alternatives to economies of scale, especially where the products satisfy the articulated needs of significant numbers of local consumers (social scale).

The paper argues that nutrient-use efficiency and water productivity can further increase in diverse production systems by integrating enterprises, tightening resource cycles and recycling, resulting in greater returns on land and labour investments and relative decoupling. Suppose the diverse range of products of many of these small production units are aggregated towards diverse small-scale processors, each processing and adding value and providing by-products to other small-scale processors for inclusion in their enterprises and generating even more products for local use. In this scenario, numerous increased social and economic returns come from the same agricultural products. Final waste products can create another range of micro-enterprises, such as biogas, compost, vermicompost and insects as protein for livestock feed (e.g., black soldier flies), creating more jobs and value-added inputs recycled to the production systems.

The economic returns per unit of such land, under such production systems, will be higher than on mono-cropped land without any livestock to increase the efficient return of biomass to land. Applying agroecological principles to transition local food systems to circularity will significantly reduce the importation of inputs and food, reduce food miles, create jobs and tighten nutrient and water cycles. This will support the local economy by cycling financial services and resources within the local food system. This level of integration, synergy and tighter resource loops, driven by locally shared visions and incentives, will pave the way for relative decoupling.

Circularity will never be absolute; some importation will always be required and excesses must be exported to strengthen local economic development. Moreover, it will improve water and nutrient use efficiencies and provide opportunities to co-create and evaluate local food system transformations. Facilitating such transitions may also alter mental models of how entire food systems can become more efficient and responsive, responding to consumer demand for more culturally acceptable food while stimulating local economies.

Agroecological-based circular food systems will not lead to food sovereignty, which requires many other factors and processes to be addressed beyond this paper's scope. Population growth rates must decline to ease pressure on land and imports. Even if growth rates fall, the population will continue to grow because of the existing youth-dominated population. At the continental scale, imports and exports will always be necessary. There needs to be a careful analysis of the allocation of land and other resources to produce food and export products. Currently, large areas of arable land and water resources are used for the production and export of food and non-food agricultural products. For Africa to be able to feed its population, there is a need to evaluate the trade-offs between allocating land for food production and producing high-value export commodities to generate foreign exchange to import what cannot be profitably grown locally. Local and international governments and trade organizations must find ways of managing these trade-offs. Africa must guard itself against companies from the Global North that sell agricultural products in SSA below local production costs, negatively affecting local value chains.

Conclusion

SSA needs to increase food production significantly to feed its population a nutritious diet by 2050 without increasing food imports. Significant biophysical factors limit the expansion of food production and productivity within the planetary boundaries, requiring new and integrated strategies to decouple food systems from natural resource use and environmental impact. Food systems' transformations towards circularity based on agroecological principles and ecological, economic and social returns on investments in scale, scope and integration are proposed to stimulate local economic, environmental and social sustainability and development. This can be operationalized by linking producers (dryland farmers and irrigators) and consumers by integrating MSMEs as food processors and users of by-products to produce inputs and recycle waste back into production systems.

There is sufficient evidence describing the diverse negative impacts of existing agricultural production systems, ranging from environmental impacts to socio-economic inequalities and poor health outcomes in the developed and developing world. Following the UN Food Systems Summit, there was agreement that food systems transformation was required, but there needs to be more clarity on what and how to do this. We need to reverse (or at least reduce) the negative impacts of existing food systems and increase rural economic development to reduce urbanization and the long-distance transportation of raw products, inputs and food. This paper proposes using irrigation and surrounding dryland production systems as central hubs for transitioning local food systems to circularity. We further propose to use the 13 principles of agroecology to co-design transitions towards circular food systems. Our earlier research confirmed that dynamic multi-stakeholder platforms can facilitate common visions among all stakeholders and address barriers to achieving these visions. Therefore, our current research-for-development project focuses on using these platforms to integrate socio-ecological transformation theory at social, institutional and technical leverage points. We aim to integrate primary and secondary producers and productivity at the farm level to ensure a sustainable resource base. Integrating small businesses through the utilization of by-products offers a pathway towards resource efficiency, economic resilience and environmental sustainability. By fostering collaboration, innovation and entrepreneurship, this approach optimizes resource utilization within local ecosystems and contributes to developing vibrant and resilient communities. Further research will be required to evaluate water, nutrient and energy flows and losses, the efficiencies achieved in returning waste to production systems, and the increased social and economic benefits. The biggest test will be evaluating the local actors' intent, capacity and incentives to change behaviour, increase cooperation and integration from plot and farm to community level, and link producers with consumers via local food processors and outlets.

Acknowledgements

This research was part of the project Transforming Small-scale Irrigation in Southern Africa (TISA) and the Circular Food Systems project (CFS), which was funded by the Australian Centre for International Agricultural Research (FSC/2013/006) and (WAC/2023/111). We thank the reviewers for their time and effort in reviewing the manuscript. We sincerely appreciate your valuable comments and suggestions, which helped us improve its quality.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Australian Centre for International Agricultural Research [FSC/2013/006] and [WAC/2023/111].

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References

Almeida, R. F., Queiroz, I. D. S., Mikhael, J. E. R., Oliveira, R. C., & Borges, E. N. (2019). Enriched animal manure as a source of phosphorus in sustainable agriculture. *International Journal of Recycling of Organic Waste in Agriculture*, *8*(S1), 203–210. https://doi.org/10.1007/s40093-019-00291-x

Betancourt, M. (2020). The effect of Cuban agroecology in mitigating the metabolic rift: A quantitative approach to Latin American food production. *Global Environmental Change*, *63*, 102075. https://doi.org/10.1016/j.gloenvcha.2020.102075

Bezner Kerr, R., Madsen, S., Stüber, M., Liebert, J., Enloe, S., Borghino, N., Parros, P., Mutyambai, D. M., Prudhon, M., & Wezel, A. (2021). Can agroecology improve food security and nutrition? A review. *Global Food Security, 29*. https://doi.org/10.1016/j.gfs.2021.100540

Bjornlund, H., van Rooyen, A., Pittock, J., Parry, K., Moyo, M., Mdemu, M., & de Sousa, W. (2020). Institutional innovation and smart water management technologies in small-scale irrigation schemes in Southern Africa. *Water International*, *45*(6), 621–650. https://doi.org/10.1080/02508060.2020.1804715

Bjornlund, V., & Bjornlund, H. (2024). Reviewing the Green Revolution strategy in view of lessons from Mexico and India–Africa. *International Journal of Water Resources Development*, 1–45. https://doi.org/10.1080/07900627.2024.2363954

Bjornlund, V., Bjornlund, H., & van Rooyen, A. (2022). Why food insecurity persists in sub-Saharan Africa: A review of existing evidence. *Food Security*, 0123456789. https://doi.org/10.1007/s12571-022-01256-1

Bjornlund, V., Bjornlund, H., & van Rooyen, A. F. (2020). Exploring the factors causing the poor performance of most irrigation schemes in post-Independence sub-Saharan Africa. *International Journal of Water Resources Development*, *36*(sup1), S54–S101. https://doi.org/10.1080/07900627.2020.1808448

Bonilla-Cedrez, C., Chamberlin, J., & Hijmans, R. J. (2021). Fertilizer and grain prices constrain food production in sub-Saharan Africa. *Nature Food*, *2*(10), 766–772. https://doi.org/10.1038/s43016-021-00370-1

Chamberlin, J., Jayne, T. S., & Headey, D. (2014). Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. *Food Policy*, *48*, 51–65. https://doi.org/10.1016/j.foodpol.2014.05.002

Chesbrough, H. (2010). Business model innovation: Opportunities and barriers. *Long Range Planning*, *43*(2–3), 354–363. https://doi.org/10.1016/j.lrp.2009.07.010

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., & Courbois Christopher Delgado, C. (2001). Livestock to 2020: The next food revolution. *Outlook on AGRICULTURE*, *30*(1), 27–29. https://doi.org/10.5367/000000001101293427

de Roest, K., Ferrari, P., & Knickel, K. (2018). Specialisation and economies of scale or diversification and economies of scope? Assessing different agricultural development pathways. *Journal of Rural Studies*, *59*, 222–231. https://doi.org/10.1016/j.jrurstud.2017.04.013

Desta, G., Kassawmar, T., Tadesse, M., & Zeleke, G. (2021). Extent and distribution of surface soil acidity in the rainfed areas of Ethiopia. *Land Degradation & Development*, *32*(18), 5348–5359. https://doi.org/10.1002/ldr.4113

Ditlev-Simonsen, C. D. (2022). Circular economy: New business models. In *A guide to sustainable corporate responsibility* (pp. 129–148). Palgrave Macmillan. https://doi.org/10.1007/978-3-030-88203-7_6

Donner, M., & de Vries, H. (2021). How to innovate business models for a circular bio-economy? *Business Strategy and the Environment*, *30*(4), 1932–1947. https://doi.org/10.1002/bse.2725

Eghbali, A. R., & Sayehmiri, A. (2022). Explaining the relationship between income and water consumption using smooth transition regression based on Kuznets' environmental theory. *Journal of Urban Management and Energy Sustainability*, *3*(2), 97–107. https://doi.org/10.22034/jumes.2022.1971451.1092

Elrys, A. S., Metwally, M. S., Raza, S., Alnaimy, M. A., Shaheen, S. M., Chen, Z., & Zhou, J. (2020). How much nitrogen does Africa need to feed itself by 2050? *Journal of Environmental Management*, *268*, 110488. https://doi.org/10.1016/j.jenvman.2020.110488

Falcon, W. P., Naylor, R. L., & Shankar, N. D. (2022). Rethinking global food demand for 2050. *Population and Development Review*, *48*(4), 921–957. https://doi.org/10.1111/padr.12508

Falkenmark, M. (1997). *Meeting water requirements of an expanding world population*. https://royalsocietypublishing.org/

FAO. (2018). *The 10 elements of agroecology: Guiding the transition to sustainable food and agricultural systems*. http://www.fao.org/3/i9037en/i9037en.pdf

Faridullah, F., Hafeez, S., Ahmed, T., Alam, S., Naz, A., Shah, W., & Khalid, S. (2018). Characterization of phosphorus in fresh and composted manures of different livestock. *Polish Journal of Environmental Studies*, *27*(2), 615–622.

Giampietro, M. (2019). On the circular bioeconomy and decoupling: Implications for sustainable growth. *Ecological Economics*, *162*, 143–156. https://doi.org/10.1016/j.ecolecon.2019.05.001

Gliessman, S. (2016). Transforming food systems with agroecology *Agroecology and Sustainable Food System, 40*, 187–189. https://doi.org/10.1080/21683565.2015.1130765

Gliessman, S. 2018. Defining agroecology. *Agroecology and Sustainable Food Systems*. *42*(6), 599–600. https://doi.org/10.1080/21683565.2018.1432329

Gliessman, S. R. (2020). Transforming food and agriculture systems with agroecology *Agriculture and Human Values, 37*, 547–548. https://doi.org/10.1007/s10460-020-10058-0

Grabau, Z. J., & Chen, S. (2016). Influence of long-term corn–soybean crop sequences on soil ecology as indicated by the nematode community. *Applied Soil Ecology*, *100*, 172–185. https://doi.org/10.1016/J.APSOIL.2015.12.016

Hamam, M., Chinnici, G., Di Vita, G., Pappalardo, G., Pecorino, B., Maesano, G., & D'Amico, M. (2021). Circular economy models in agro-food systems: A review. *Sustainability (Switzerland)*, *13*(6). https://doi.org/10.3390/su13063453

Harder, R., Giampietro, M., & Smukler, S. (2021). Towards a circular nutrient economy. A novel way to analyze the circularity of nutrient flows in food systems. *Resources, Conservation and Recycling*, 172. https://doi.org/10.1016/j.resconrec.2021.105693

Hayashi, K. (2011). A new conceptual framework for assessing rural development performance: Sustainability of scale, scope and integration. In M. Behnassi, S. Draggan, & S. Yaya (Eds.), *Global food insecurity* (pp. 3–9). Springer Netherlands. https://doi.org/10.1007/978-94-007-0890-7_1

HLPE. (2019). *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the high level panel of experts on food security and nutrition of the committee on world food security, Rome*. www.fao.org/cfs/cfs–hlpe

Hulett, J. L., Weiss, R. E., Bwibo, N. O., Galal, O. M., Drorbaugh, N., & Neumann, C. G. (2014). Animal source foods have a positive impact on the primary school test scores of Kenyan schoolchildren in a cluster-randomised, controlled feeding intervention trial. *British Journal of Nutrition*, *111*(5), 875–886. https://doi.org/10.1017/S0007114513003310

Ibeawuchi, I. I. (2007). Landrace legumes: Synopsis of the culture, importance, potentials and roles in agricultural production systems. *Journal of Biological Sciences*, *7*(3), 464–474. https://doi.org/10.3923/jbs.2007.464.474

IPES-Food. (2018). *Breaking away from industrial food and farming systems: Seven case studies of agroecological transition*. www.ipes-food.org

Jurgilevich, A., Birge, T., Kentala-Lehtonen, J., Korhonen-Kurki, K., Pietikäinen, J., Saikku, L., & Schösler, H. (2016). Transition towards circular economy in the food system. *Sustainability (Switzerland)*, *8*(1). https://doi.org/10.3390/su8010069

Kass, D. C. L. (1996). Agroecology: The science of sustainable agriculture. *Agroforestry Systems*, *35*(1), 111–115. https://doi.org/10.1007/BF02345332

Kihara, J., Bolo, P., Kinyua, M., Rurinda, J., & Piikki, K. (2020). Micronutrient deficiencies in African soils and the human nutritional nexus: Opportunities with staple crops *Environmental Geochemistry and Health, 42*, 3015–3033. https://doi.org/10.1007/s10653-019-00499-w

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*(April), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kuhn, A., & Britz, W. (2021). Long-term scenarios for sub-Saharan Africa's agro-food markets with varying population, income, and crop productivity trends. *Journal of Agricultural and Resource Economics*, *46*(1), 20–36. https://doi.org/10.22004/ag.econ.304766

Latino, L. R., Pica-Ciamarra, U., & Wisser, D. (2020). Africa: The livestock revolution urbanizes. *Global Food Security*, *26*, 100399. https://doi.org/10.1016/j.gfs.2020.100399

Lever, J., & Sonnino, R. (2022). Food system transformation for sustainable city-regions: Exploring the potential of circular economies. *Regional Studies*, *56*(12), 2019–2031. https://doi.org/10.1080/00343404.2021.2021168

Magnone, D., Niasar, V. J., Bouwman, A. F., Beusen, A. H. W., van der Zee, S. E. A. T. M., & Sattari, S. Z. (2022). The impact of phosphorus on projected Sub-Saharan Africa food security futures. *Nature Communications*, *13*(1). https://doi.org/10.1038/s41467-022-33900-x

McGlashan, J., de la Haye, K., Wang, P., & Allender, S. (2019). Collaboration in complex systems: Multilevel network analysis for community-based obesity prevention interventions. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-47759-4

Mdemu, M., Kissoly, L., Bjornlund, H., Kimaro, E., Christen, E. W., van Rooyen, A., Stirzaker, R., & Ramshaw, P. (2020). The role of soil water monitoring tools and agricultural innovation platforms in improving food security and income of farmers in smallholder irrigation schemes in Tanzania. *International Journal of Water Resources Development*, 1–23. https://doi.org/10.1080/07900627.2020.1765746

Mdemu, M. V., Kimaro, E. G., Tafula, M., de Sousa, W., Moyo, M., Parry, K., Bjornlund, H., Mukwakwami, N., & Ramshaw, P. (2023). Participatory mapping of irrigation schemes in Tanzania, Mozambique and Zimbabwe and their value for multi-level learning. *Agricultural Water Management*, *290*, 108591. https://doi.org/10.1016/j.agwat.2023.108591

Mdemu, M. V., Mziray, N., Bjornlund, H., & Kashaigili, J. J. (2017). Barriers to and opportunities for improving productivity and profitability of the Kiwere and Magozi irrigation schemes in Tanzania. *International Journal of Water Resources Development*, *33*(5), 725–739. https://doi.org/10.1080/07900627.2016.1188267

Morais, T. G., Teixeira, R. F. M., Lauk, C., Theurl, M. C., Winiwarter, W., Mayer, A., Kaufmann, L., Haberl, H., Domingos, T., & Erb, K. H. (2021). Agroecological measures and circular economy strategies to ensure sufficient nitrogen for sustainable farming. *Global Environmental Change*, *69*, 102313. https://doi.org/10.1016/j.gloenvcha.2021.102313

Moyo, M., Van Rooyen, A., Bjornlund, H., Parry, K., Stirzaker, R., Dube, T., & Maya, M. (2020). The dynamics between irrigation frequency and soil nutrient management: Transitioning smallholder irrigation towards more profitable and sustainable systems in Zimbabwe. *International Journal of Water Resources Development*, (1), 1–25. https://doi.org/10.1080/07900627.2020.1739513

Muscat, A., de Olde, E. M., Ripoll-Bosch, R., Van Zanten, H. H. E., Metze, T. A. P., Termeer, C. J. A. M., van Ittersum, M. K., & de Boer, I. J. M. (2021). Principles, drivers and opportunities of a circular bioeconomy *Nature Food, 2*, 561–566. https://doi.org/10.1038/s43016-021-00340-7

Nika, C. E., Vasilaki, V., Expósito, A., & Katsou, E. (2020). Water cycle and circular economy: Developing a circularity assessment framework for complex water systems. *Water Research*, *187*, 116423. https://doi.org/10.1016/j.watres.2020.116423

Onyutha, C. (2018). African crop production trends are insufficient to guarantee food security in the sub-Saharan region by 2050 owing to persistent poverty. *Food Security*, *10*(5), 1203–1219. https://doi.org/10.1007/s12571-018-0839-7

Pittock, J., Bjornlund, H., & van Rooyen, A. (2020). Transforming failing smallholder irrigation schemes in Africa: A theory of change. *International Journal of Water Resources Development*, *36*(sup1), S1–S19. https://doi.org/10.1080/07900627.2020.1819776

Salvador, R., Puglieri, F. N., Halog, A., Andrade, F. G. D., Piekarski, C. M., & De Francisco, A. C. (2021). Key aspects for designing business models for a circular bioeconomy. *Journal of Cleaner Production, 278*. https://doi.org/10.1016/j.jclepro.2020.124341

Sanchez, P. A. (2002). Soil fertility and hunger in Africa. *Science*, *295*(5562), 2019–2020. https://doi.org/10.1126/science.1065256

Scheel, C., Aguiñaga, E., & Bello, B. (2020). Decoupling economic development from the consumption of finite resources using circular economy. A model for developing countries. *Sustainability (Switzerland)*, *12*(4). https://doi.org/10.3390/su12041291

Schroeder, P., Anggraeni, K., & Weber, U. (2019). The relevance of circular economy practices to the sustainable development goals. *Journal of Industrial Ecology*, *23*(1), 77–95. https://doi.org/10.1111/jiec.12732

Sijpestijn, G. F., Wezel, A., & Chriki, S. (2022). Can agroecology help in meeting our 2050 protein requirements? *Livestock Science*, 256. https://doi.org/10.1016/j.livsci.2022.104822

Sileshi, G. W., Kihara, J., Tamene, L., Vanlauwe, B., Phiri, E., & Jama, B. (2022). Unravelling causes of poor crop response to applied N and P fertilizers on African soils. *Experimental Agriculture, 58*. https://doi.org/10.1017/S0014479721000247

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., & De Haan, C. (2006). *Livestock's long shadow: Environmental issues and options*. (Vol. 24, Issue A0701/E). FAO. http://www.fao.org/docrep/010/a0701e/a0701e00.htm

Tan, E. C. D., & Lamers, P. (2021). Circular bioeconomy concepts—A perspective. *Frontiers in Sustainability*, 2. https://doi.org/10.3389/frsus.2021.701509

UNEP. (2011). *Decoupling natural resource use and environmental impacts from economic growth : An excerpt of the report*.

van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P. A. J., van Loon, M. P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., & Cassman, K. G. (2016). Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences*, *113*(52), 14964–14969. https://doi.org/10.1073/pnas.1610359113

van Rooyen, A. F., Moyo, M., Bjornlund, H., Dube, T., Parry, K., & Stirzaker, R. (2020). Identifying leverage points to transition dysfunctional irrigation schemes towards complex adaptive systems. *International Journal of Water Resources Development*, *36*(sup1), S171–S198. https://doi.org/10.1080/07900627.2020.1747409

van Rooyen, A. F., Ramshaw, P., Moyo, M., Stirzaker, R., & Bjornlund, H. (2017). Theory and application of Agricultural Innovation Platforms for improved irrigation scheme management in Southern Africa. *International Journal of Water Resources Development*, *33*(5), 804–823. https://doi.org/10.1080/07900627.2017.1321530

van Straaten, P. (2011). The geological basis of farming in Africa. In A. Bationo, B. Waswa, J. Okeyo, F. Maina, & J. Kihara (Eds), *Innovations as Key to the Green Revolution in Africa* (pp. 31–47). Springer Netherlands. https://doi.org/10.1007/978-90-481-2543-2_3

Van Zanten, H. H. E., Van Ittersum, M. K., & De Boer, I. J. M. (2019). The role of farm animals in a circular food system. *Global Food Security*, *21*, 18–22. https://doi.org/10.1016/j.gfs.2019.06.003

Velasco-Muñoz, J. F., Mendoza, J. M. F., Aznar-Sánchez, J. A., & Gallego-Schmid, A. (2021). Circular economy implementation in the agricultural sector: Definition, strategies and indicators. *Resources, Conservation and Recycling*, 170. https://doi.org/10.1016/j.resconrec.2021.105618

Venkata Mohan, S., Nikhil, G. N., Chiranjeevi, P., Nagendranatha Reddy, C., Rohit, M. V., Kumar, A. N., & Sarkar, O. (2016). Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives. *Bioresource Technology, 215*, 2–12. https://doi.org/10.1016/j.biortech.2016.03.130

Wang, P., Robins, G., Pattison, P., & Lazega, E. (2013). Exponential random graph models for multi-level networks. *Social Networks*, *35*(1), 96–115. https://doi.org/10.1016/j.socnet.2013.01.004

Wellington, M., Kuhnert, P., Lawes, R., Renzullo, L., Pittock, J., Ramshaw, P., Moyo, M., Kimaro, E., Tafula, M., & van Rooyen, A. (2023). Decoupling crop production from water consumption at some irrigation schemes in Southern Africa. *Agricultural Water Management*, 284. https://doi.org/10.1016/j.agwat.2023.108358

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., & David, C. (2009). Agroecology as a science, a movement and a practice. A review. *Agronomy for Sustainable Development*, *29*(4), 503–515. https://doi.org/10.1051/agro/2009004

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, *40*(6), 1–13. https://doi.org/10.1007/S13593-020-00646-Z/FIGURES/5

Xie, H., Perez, N., Anderson, W., Ringler, C., & You, L. (2018). Can Sub-Saharan Africa feed itself? The role of irrigation development in the region's drylands for food security. *Water International*, *43*(6), 796–814. https://doi.org/10.1080/02508060.2018.1516080

Xie, H., You, L., Wielgosz, B., & Ringler, C. (2014). Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. *Agricultural Water Management*, *131*, 183–193. https://doi.org/10.1016/j.agwat.2013.08.011

Zhang, Q., Dhir, A., & Kaur, P. (2022). Circular economy and the food sector: A systematic literature review *Sustainable Production and Consumption, 32*, 655–668. https://doi.org/10.1016/j.spc.2022.05.010

Zucchella, A., & Previtali, P. (2019). Circular business models for sustainable development: A "waste is food" restorative ecosystem. *Business Strategy and the Environment*, *28*(2), 274–285. https://doi.org/10.1002/bse.2216