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Towards a green plant nutrition transition in East and Southern Africa

Philip Thornton[1*], **Ana Maria Loboguerrero**[2], **Senni Alho**[1], **Bruce Campbell**[1], **Dhanush Dinesh**[1], **Ulrich Helberg**[3], **Jon Hellin**[4], **Bruno Partridge**[5], **Frank Rasche**[6], **Zachary Stewart**[7], **Leanne Zeppenfeldt**[1]

1 Clim-Eat, Wageningen, The Netherlands, **2** Gates Foundation, Washington, District of Columbia, United States of America, **3** Helberg Consult, Witzenhausen, Germany, **4** International Rice Research Institute, Los Baños, Philippines, **5** C'Nergy Africa Ltd, Lilongwe, Malawi, **6** International Institute of Tropical Agriculture, Nairobi, Kenya, **7** International Fertilizer Development Center, Muscle Shoals, Alabama, United States of America

* p.thornton@cgiar.org

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Abstract

The abundance of renewable energy in East and Southern Africa offers considerable opportunities for countries to transition towards green economies. In particular, green plant nutrition could help to greatly reduce greenhouse gas emissions from fertilizer and food production, and deliver environmental, balance of trade and climate resilience benefits while helping to meet future food demand. Here we discuss the viability of a green nutrition transition in the region in relation to current constraints and bottlenecks in different locations. A green nutrition transition will require careful management so that knowledge and assets can be shared in ways that neither marginalise some agricultural producers and input suppliers nor worsen power asymmetries in communities. Inclusive and participatory processes will be required to help align often competing narratives and objectives at local and national levels and, where feasible, to modify institutional and power structures for the common good. We outline several concrete actions that could contribute to the green nutrition transition, including filling evidence gaps and carrying out ex ante and ex post impact studies, bringing together the public and private sectors in convenings to design and implement pilot studies, and exploring agricultural input subsidy realignment and other incentives with national governments and the private sector. Initiatives such as the Africa Fertilizer and Soil Health Action Plan and regional climate action plans provide solid frameworks for a wide range of activities, and the continent could lead the way in greening plant nutrition to the benefit of people and planet.

1 Introduction

Most of the increase in the demand for food to the middle of this century is projected to come from lower-income countries, particularly those of sub-Saharan Africa

(SSA) and Asia, because of growing populations, increasing urbanization and rising incomes. Over 70% of cultivated African soils are degraded, with nutrient losses of 30–60 kg per ha annually, valued at USD 4 billion. Without intervention, half of the region's arable land could become unusable by 2050. At the same time, fertiliser use in SSA is less than 20 kg per ha, far below the global average of 135 kg per ha, leading to persistently low crop yields and food insecurity. Fertiliser prices in SSA are 2–3 times higher than global averages, driven by high import costs, logistics, and market inefficiencies. Current fertiliser production systems rely on energy-intensive Haber-Bosch processes, contributing nearly 2% of global greenhouse gas (GHG) emissions [1]. While inorganic fertilisers will continue to play a major role in crop production for the foreseeable future, these challenges need urgent attention.

In recent years, the potential role of green(er) plant nutrition in helping to greatly reduce GHG emissions from food production as well as delivering environmental and climate resilience benefits while helping to meet future food demand, has come increasingly to the fore. In the African context, green plant nutrition could increase the quantity and resilience of food supply for growing populations while at the same time contributing to countries' Nationally Determined Contributions to reduce GHG emissions under the Paris Agreement. It is useful to distinguish between two sides of the green nutrition equation: what might be termed the fertiliser production side and the fertiliser utilisation/ plant demand side. For the first, considerable progress is being made in decarbonising the manufacturing of ammonia, the precursor to inorganic nitrogen fertiliser, using variants of the highly energy-intensive Haber-Bosch process, invented more than a century ago, together with renewable energy sources rather than the traditional fossil fuels [2–5]. For the second, a wide variety of technologies and management methods exist, or are in development, that can be used to supplement (or in some situations, replace the need for) inorganic fertiliser and/ or to increase the efficiency with which it is utilised by the plant. These technologies and management methods span the range from the old and well-studied, such as intercropping cereals with legumes and adding organic material (compost, animal manure) to the soil, to the new and largely untested at scale, such as silicon-based fertiliser [6] and biofertiliser technology [7]. In what follows, we place all of these technologies and management methods, old and new, along with fertiliser production technologies that use renewable energy, under the umbrella of "green (plant) nutrition". This includes innovative technologies such as plasma-assisted fertiliser production; see https://foodsystems.tech/ for several examples.

Whether technologies address the fertiliser production or the utilisation side, the benefits of green nutrition may be considerable: reduced GHG emissions from production, processing and transportation of fertiliser that use renewable sources of energy; soil fertility restoration; increased yields and climate resilience for farmers; and reduced prices for urban consumers, to name a few. A green nutrition transition has considerable potential in improving fertiliser accessibility and affordability for smallholder farmers. It further raises the possibility of fertiliser production that is both small-scale and decentralised, hitherto largely impossible for many lower-income countries. The savings of scarce foreign exchange in many countries from avoiding fertiliser imports could be very large: for instance, up to half of the Malawi's Ministry of Agriculture budget is spent on importing fertiliser, and the country's fertiliser subsidies, in the pursuit of national food production objectives, account for a significant portion of national GDP [8]. Local and small-scale fertiliser production could greatly increase small-scale farmers' timely access to affordable N fertiliser, particularly in more remote rural areas, as well as reducing countries' high dependence on imports, thus helping to reduce their exposure to global market shocks [9].

Here we consider the viability of a green nutrition transition in the countries of East and southern Africa to address the urgent issues outlined above, in relation to current constraints, bottlenecks and opportunities, under five headings: local context, inclusive extension, politics, the knowledge base, and transitioning to impact. We conclude with a brief discussion of actions that may help to facilitate the transition in the region.

2.1 Local context

Syntheses of the very large literature on the adoption of agricultural technology in sub-Saharan Africa highlight the critical importance of local context in determining uptake [10–12]. Many biophysical and socio-economic variables have been identified that help to explain adoption of particular technologies in different places; a few are common across many contexts, but many are not, and there are none that are universal predictors. In the same way that there are no technological or management silver bullets that can address all the problems of African agriculture, neither are there options that are applicable everywhere. Enormous local and regional variation exists in the natural resources (such as topography, soil quality and rainfall and other water resources) in African farming systems, and the same is true of cultural and socio-economic variation [13]. The local context has to be taken into account in tailoring specific technologies and management options to specific circumstances. Doing this appropriately will usually involve targeting beneficiaries across the fertiliser value chain and/or the food system, and if there are multiple options to be considered, evaluating these with respect to their different priorities.

But in any context, these priorities can vary widely: farmers may prioritise more yield, more yield stability and higher incomes; government may prioritise domestic food production while preserving scarce foreign exchange for other essentials such as fuel; and the research and development (R&D) community may prioritise improving fertiliser response in farmers' fields in the face of declining or stagnating yields while input use is being increased, for example. Any actions designed for helping transition to greener plant nutrition thus need to be firmly set within the local context and involve identifying priorities that mesh with different objectives, while also recognizing the heterogeneity of these objectives. An illustration of this is provided by colleagues [14] with respect to targeting soil health practices in Malawi. Rather than trying to improve soil health on all fields through agronomy and inputs, actions might better be focused on maintaining soil health in the more productive areas, rehabilitating marginally degraded areas, and preserving other and more degraded lands for nature, where possible. The costs and benefits of these different actions vary widely on different soils, but the returns on investment in the overall approach are likely to greatly exceed the returns from a blanket approach that ignores soil variation. Such an approach does not mean leaving behind the farmers on heavily degraded soils - but it does mean that different options will likely be required to maintain and enhance their livelihoods. Even in more productive areas, care will also be needed to mitigate the dangers of maladaptation [15] whereby those who benefit from a green plant transition do not do so at the expense of more vulnerable farmers.

Another example is the potential siting of small-scale green ammonia plants in East and Southern Africa. Two (of many) prerequisites for a viable site are an adequate and reliable supply of water and access to a reliable supply of renewable energy. Taken together, some 17% of the total value of current crop production in Burundi, Ethiopia, Kenya, Rwanda, Malawi and Uganda comes from areas with both adequate water supplies and high availability of solar, hydro and/or geothermal resources for powering green ammonia plants [16]. Of course, the economic viability of small-scale ammonia production will depend on many other factors, such as the capital costs required and the costs of converting green ammonia into a product that can be used by farmers, for example [17].

The technologies for a green nutrition transition, as for all agricultural technologies, need to strike a balance between increasing reach for broader impact on the one hand, and addressing context specificity on the other. In some situations, prioritizing options at appropriate scale may be time consuming but will still be needed if sub-optimal returns on investment are to be avoided. On the upside, the East and Southern Africa region has a very considerable knowledge base concerning agronomy and soil fertility extending over many decades and is relatively data rich, compared with most other regions of the continent. Much can still be learned from this knowledge base to help farmers fertilise their crops according to the needs of the plant and farmers' resources, rather than using blanket recommendations, but considerable expansion in consistent soil testing and analysis may still be needed, regardless of the source of the nutrients. At the same time, one way in which the fertilizer industry might be incentivised to meet the diverse needs of small-scale producers, crops, soils and climates with respect to microbial and other novel fertilisers, is through the development of open-access methodologies for validating, characterizing, producing and utilising them. The widespread adoption of standardized protocols across both public and private sectors could help ensure that biofertilizers are consistently profitable for smallholder farmers.

2.2 Inclusive extension

At least in the shorter term, all innovation results in winners and losers [18]. The importance of considering the unintended consequences of technological innovation in food systems is critically important. There are many examples of new technology exacerbating existing inequalities and hardening power asymmetries, whereby the benefits are captured by one group and other members of agricultural communities are left behind [19]. Guarding against unintended consequences of food system innovation may take several forms. The tools and methods of interdisciplinary research and rights-based development approaches can help in anticipating the likely effects of technology uptake on equity and vulnerable and excluded groups of people, so that the benefits of innovation can be shared by all [20]. A key part of this is ensuring that all voices are heard. At the same time, given the complexity of food systems, it will rarely be possible to anticipate all the effects of innovation. Thus, secondly, safeguarding against undesirable impacts will almost always be needed, involving monitoring the uptake of innovation and assessing its effects on farmer incomes, gender equity, market prices, and input accessibility, among many others. In some cases, it may be necessary to make corrections to the enabling environment to ensure equitable access to the benefits of innovation, through additional knowledge transfer to specific groups or provision of temporary financial incentives, such as cheaper farm credit or higher farm prices, to encourage early uptake, for example [21].

Most if not all of the technologies that are or may be appropriate for fostering a green nutrition transition are relatively knowledge intensive. This applies to well-studied options such as cereal-legume intercropping and composting as well as to novel technologies such as new fertiliser materials and production practices. Some may be more resource intensive as well, with respect to labour and capital needs. Effective public and private extension systems will thus be a critical component of any inclusive transition. In many countries, extension services are currently heavily under-resourced – again using Malawi as an example, a mere 5% of the Ministry of Agriculture's budget is spent on extension. A further element is ensuring that what extension services are promoting actually fits with government objectives; this is not always the case [22].

Several scalable extension models exist, which can take local context into account while being replicable to extend reach. These include farmer field schools and related efforts; an example is in Zambia, where learning agendas are being scaled out with women and young people being reached through a combination of digital champions and ICT apps. Burundi has an extension system that uses village-based advisors or relay farmers, who are regularly trained by local agronomists. Madagascar has a similar system, along with a dedicated research centre where relay farmers can attend demonstrations and extensionists are continuously trained. The use of a village-based advisory system can magnify reach considerably, although ensuring stable financial support can be challenging. Linking up village-based advisors with local agri traders and being able to offer bundled services to farmers as well as expanding the use of ICT apps and tools, may be effective in this regard. Another example is CARE's Farmer Field and Business School (FFBS) model [23], an extension model that combines agronomics with market, nutrition, and women's empowerment interventions. A particular feature of the FFBS model is that it targets discriminatory gender norms that limit women's meaningful participation, leadership, and financial benefits. Another high-potential growth area is dialogue platforms based on ICTs; these are already facilitating the transfer of extension information in several countries. Such platforms are helping to connect farmers, consumers and extension services, and are already reaching several million producers in the region, many of them women and young people.

2.3 Politics

A green nutrition transition in East and southern Africa will need considerable political commitment on the part of the national governments involved. During the Africa Fertiliser and Soil Health Summit in 2024, leaders committed to tripling domestic fertiliser production on the continent, and there is an opportunity to reduce the possible adverse effects on the environment of this increase in production. The issues raised in section 2.1 above, on priority setting and public-sector investment in actions that can promote the green nutrition transition in ways that align with governmental objectives, and in section 2.2 on public-sector knowledge transfer to producers and other value chain actors, need political commitment. The repurposing of subsidies has often been identified as a key action for the climate action and food systems transition agenda. Public support for agricultural producers in 51 countries covering the period 2015–2017 amounted to USD 570 billion; in many cases these were distortionary, resulting in negative environmental and climate impacts, and low return on investment [24]. There is considerable potential in realigning even some of these subsidies in such a way as to support a green nutrition and other food system transitions, perhaps coupled with providing incentives for the generation, storage and utilisation of renewable energy. Recent unpublished work from the Gates Foundation indicates that if countries were to fully reallocate fertiliser subsidy expenditure to capital expenditure for green ammonia or plasma nitrates, they could be self-sufficient in fertiliser production within a few years. For example, Ethiopia spent nearly USD 292 M on fertiliser subsidies in 2024. Depending on the technologies used, between USD 400 M and USD 1 B of capital expenditure would be sufficient to satisfy domestic N demand via green ammonia/ plasma nitrate production.

Because most of the countries in the region rely on imported fertiliser, given the scale required, its supply is controlled by a few multinational corporations. Bringing about shifts in the status quo via the entry of new, decentralised and smaller-scale fertiliser production systems may be difficult to achieve. The political economy issues associated with elite alliances in the sector that need to be addressed should not be underestimated [25].

But shifts can occur. For example, in the veterinary medicines space in Africa, the entry of smaller, regional pharmaceutical companies (rather than the multinationals) that manufacture and distribute animal vaccines is increasing their access by small-scale livestock producers while decreasing import dependency. Another is the ongoing discussion and planning on reorientating the inorganic fertiliser subsidy program in Malawi [8]. The existing subsidy program is not delivering on food security goals, partly because soil health in many parts of the country is declining due largely to lack of organic matter in the soil. The Malawi government is trialling incentives for soil health management (addition of legumes to the farming system, composting, fallowing, rotations), including a payment for ecosystems services (PES) scheme, with the intention that these would, if successful, be funded through reducing the inorganic fertiliser subsidy. The pilot involves 24,000 farmers and includes low-cost monitoring and reporting of soil health to ensure that practice payments are actually delivering, as well as leveraging private sector investment in fertilisers to enhance soil health. All this has involved a great deal of personal interaction at the highest levels of government in the country: policy makers, researchers and the private sector sitting down at the table and discussing the details of how to make this work. Government commitment is critical, and countries like Malawi are showing one way forward

There are no obvious short-cuts to obtaining government buy-in and commitment to investments that can deliver multiple benefits. Multi-party support will be key to weathering government transitions and other times when political goals come to the fore. Despite the challenges, there are some mechanisms that may be able to help these processes.

These include science-policy dialogue and innovation platforms, which include local farmers, agri dealers, researchers and national policy advisors [26]. Such platforms already exist in some countries of East and West Africa and have been shown to be effective in facilitating dialogue and passing information on issues and challenges between the local and national levels. Another is participatory scenario building and future visioning processes, which can help to align competing objectives, address future uncertainties, and create spaces for action [27]. There is also the tailoring of support to countries to encourage them to undertake a reform agenda. This could involve implementing information and communications strategies designed to achieve a consensus for reform, as well as providing technical assistance to identify the most appropriate leverage points for policy reform and investment action and implementation [28].

2.4 Knowledge base

The knowledge base concerning the costs and benefits of a green nutrition transition in the region is not complete. There are several issues that need to be addressed with respect to research and development. Contextualized soil management is key to increasing the use efficiency of inorganic fertiliser. This implies reducing the losses that may occur through reaction of the fertiliser in the soil, matching better the demand for nutrients by the crop with their supply, and avoiding runoff and leaching of the fertiliser applied without its being taken up the plant. An important aspect of N use efficiency is the form in which the N is applied. Urea is the most common form of nitrogen fertiliser used in Africa, but its use is often accompanied by heavy and rapid losses of N to the atmosphere via volatilization and runoff if conditions are not favourable (e.g., dry soils, high pH). In smallholder situations, using a urease inhibitor to delay volatilisation will often not be viable, but in some situations nitrate-based fertilisers can significantly reduce N losses in the field. Better understanding of the soil, health, environmental and economic benefits of using nitrates compared with urea under smallholder conditions is needed.

Additional research is still needed that can test and validate the performance of some of the novel green nutrition technologies under different conditions in the region and their effects on soil health, the environment and farm profitability, in terms of both their utilisation and production. For green N production, this includes studies on its feasibility at small scale with respect to energy and water storage and use. Infrastructure to store renewable energy relatively cheaply, using high-efficiency batteries or novel thermal storage methods, could allow fertiliser production in places where national energy grids do not yet exist [1]. In practice, about 1.2-1.5 kg of water is needed to produce 1 kg of green ammonia [29]. In addition, the technology for transforming the gaseous or liquid products of green ammonia synthesis into a granular (or other) form for smallholder farmers is still under development. Cost-effective granulation methods are needed that can supply appropriate N products via existing fertiliser distribution pathways. In some cases, new distribution networks may need to be developed.

New models are being proposed that could assist in making green technologies more available in SSA. One example is the foundry model, a business model originating in the world of microelectronics in which the “foundry” company makes the semiconductors and a separate company makes the integrated circuits. Such an approach could be used for decentralized green fertiliser, providing a sandbox for experimentation and assisting more companies to apply their technology in SSA, through providing core inputs such as land, water and power, along with market research for experimentation and de-risking.

There is considerable work to be done to raise general awareness of green nutrition. Research institutes have an important role in helping to strengthen the evidence base, and in helping to develop appropriate communications materials, concerning the benefits of a green nutrition transition, to raise awareness of investors, the private sector and governments. This will include developing solid business cases for investment in and deployment at scale of green fertilisers. This will mean developing the capacity of small and medium-sized enterprises (SMEs) and local service providers to support the marketing, distribution, and scaling of green fertiliser technology. This could provide new employment opportunities in rural areas. There is also considerable potential in integrating new technologies into policy forums and regional frameworks such as the African Union's Soil Health Agenda [9], to help raise awareness and incentivize political commitments.

The decentralised production of green ammonia as a precursor of green N raises some utilisation issues. First, ammonia is the basis from which other more stable types of N fertiliser are derived. More research is needed to explore cost-effective decentralized solutions for converting both gas and aqueous ammonia into a safe and usable form. This is not currently a priority for fertiliser companies with a focus on commercial agriculture. There is a need for prioritised funding of appropriate research, ensuring that any new products are in a high N density form and that they are applicable in the African context. Second and related, there are safety issues, given that ammonia is a corrosive and toxic substance, although there are well-established industry best practices for mitigating human health and environmental risks in its production [30]. Safety training will be needed in its production, handling and transportation at the production site and, depending on how N is formulated for use by farmers, further down the value chain. This may require some form of certification scheme to minimize the risk of accidents. New fertiliser products will require effective extension about their efficient use, and training farmers in how to utilise these new products safely to improve crop response, soil health and profitability will be key.

2.5 Transitioning to impact

Several African countries are already implementing projects to develop green hydrogen facilities with the aim of producing fertilizer and other products, and some of this production is targeted for export to Europe and elsewhere, thereby increasing foreign exchange earnings [31]. An alternative or complementary objective for countries whose economies have a high dependence on agriculture is to decrease the yield gap. There will be many more people to feed in SSA by mid-century. More than seventy years of agronomic research in the region has demonstrated a wide range of options to improve and maintain soil health that are effective and sustainable, many involving organic and inorganic fertilisers. The options are multiplying: ongoing R&D is providing new and more sustainable ways of producing inorganic fertilisers and new types of fertiliser altogether. Utilizing these resources efficiently and effectively is crucial for enhancing the soil resource base on which cropping largely depends.

As noted in section 2.1, there is no single technology that will be effective everywhere, and different contexts will require different combinations of available options to achieve soil health – mixtures of bio-, organic and/or inorganic fertilisers as well as a host of different management options such as fallowing and legume intercropping. There are many factors that will determine the appropriate mix of options in any context: soil type, weather and climate, agricultural system, social context and market conditions, to name just a few. The mix will change spatially at almost any scale: nationally, district-wise, within a village.

Identifying the mix of options that will be appropriate in particular contexts is not straightforward and may require considerable efforts in convening prospective partners from government, research, the private sector, prospective funders and farming communities, to work towards a consensus around the activities needed and details of how they can be implemented. Once acceptable plans or pilots for green nutrition actions have been designed and implementation is underway, the need to monitor performance becomes crucial. As noted above, monitoring of key indicators on crop production and income levels, environmental conditions, equity measures, and resource use and access, will be key in helping to identify not only success but also unintended consequences. There is certainly scope within a green nutrition transition in a country to have unwanted effects (in addition to the aforementioned dangers of maladaptation). For example, one of the perverse incentives of cheaper N fertiliser that has been observed in some situations is that it can lead to excessive use, declining N use efficiency and little effect on GHG emissions. Experience with carbon farming projects elsewhere indicates that poor and marginalised farmers are often excluded [32]. In such cases, corrective action may be indicated: for N overuse, this might involve more farmer training on optimal N use; in the case of carbon farming, temporary pricing differentials may encourage poorer farmers to start taking part.

Green transition projects in the region will require finance, both for piloting and for taking to scale. In addition to subsidy realignment as outlined in the Malawi example (section 2.3), there are other sources of prospective finance for green nutrition support. In some countries, the availability of further soft loans from the development banks may be limited because existing debt distress. In addition, as noted above, foreign currency reserves may be limited because of negative trade balances, resulting in an inability to finance further imports. Other sources of finance may include development assistance, several climate funds, and philanthropic organisations. Accessing such sources can take considerable time and effort, and most will depend on plausible business cases and appropriately estimated returns on investment. Business cases could be built around a range of different push and pull mechanisms. Push incentives that can promote green nutrition innovation include grants, research and development tax credits, and public funding for national research organisations and basic science. Pull incentives can increase returns on investment and/or decrease investment risk, and these include volume guarantees and various "pay for results" methods [1].

One option for financing that could be developed further is in relation to carbon markets. Centralised fertiliser manufacturing processes based on the Haber-Bosch process can produce nearly 3 t CO_2 per t of ammonia, and nearly 30% of these emissions come from transportation. Decentralized manufacturing plants utilizing electrolyzers powered by solar energy have achieved emissions as low as 0.12 t CO_2 per t of ammonia, and a plasma nitrates company reports emissions of 0.16 t of CO_2 per t of N for its calcium nitrate process. Monetizing these emission reductions through carbon markets could generate significant revenue and support the adoption of these technologies in different places. Currently, however, Africa's carbon markets are heavily underdeveloped and represent a mere 2% of global trading, with most activity occurring in voluntary carbon markets. Until such a time as carbon offset prices increase considerably from their typical level of <USD 10 per t, the financial incentives for such initiatives will remain very limited.

A green nutrition transition is not without risks. As noted above, government commitment is critically important, so that policies and both public and private investment are aligned. The Malawi pilot initiative outlined in section 2.3 provides a good example of the processes that may be needed to encourage governments to commit to a green nutrition transition. It also nicely illustrates the potential benefits of bundling, in this case incorporating a payments scheme for soil health actions and carbon farming. In some situations, other opportunities may exist for bundling as well, including energy farming and agrivoltaics. Lack of government commitment may stall the whole process of a green nutrition transition.

Another risk is that the mix of options that is appropriate in one context may change through time: this is probably inevitable but becomes particularly challenging when change happens relatively rapidly. For example, new or more effective technological options become available, or the capital cost of green N production declines, or local markets are growing and diversifying, or government priorities are modified as a result of political pressures or a new government. At the same time, rapidly-evolving technologies may provide new opportunities for entrepreneurs and companies to develop profitable business cases for new investment. Impacts and priorities may need to be continually reassessed. Fairly rapid changes in the relative costs and benefits of centralised versus decentralised green N production can be envisaged in the near future because the technology is continually evolving, for instance. There may be public economies of scale to more centralised production, through more private benefits to localised production via cheaper and more accessible fertilisers, depending on local context.

3 Next steps

The major actions and opportunities outlined above for a green nutrition transition in the region are summarised in Table 1, linked to the appropriate subsection and challenges outlined above. Some of the actions address more than one challenge. These actions span a wide range of food system actors as well as multiple scales, from the local to the national and regional. Like any major food system change, a green plant nutrition transition will depend on a host of individual, social and economic processes that succeed in merging bottom-up and top-down action [21,33].

Table 1. Possible actions to support a green nutrition transition in East & Southern Africa. The areas and challenges refer to the subsections in the essay.

Area	Challenge	Possible Actions
2.1 Local Context	How to address biophysical, socio-economic and cultural variability and differences	• Address key evidence gaps concerning the costs & economic, environmental, social benefits of different green nutrition technologies in different contexts (also **2.4)** • Exploit the existing knowledge base and develop tools and protocols to inform soil health practices and nutrient needs at local level (also **2.4**) • Carry out baseline impact evaluations for pilot activities (also **2.5)**
2.2 Inclusive extension	How to share knowledge and assets in ways that do not marginalise some stakeholders and worsen power asymmetries in communities	• Explore opportunities to bundle green nutrition options with other input supplies, PES, and C and energy farming (also **2.5)** • Develop and implement novel and inclusive extension models to take innovations to scale
2.3 Politics	How to better align often competing narratives and objectives and diverse institutional/ power structures for the common good	• Use dialogue platforms for stakeholder convenings for pilot activities • Explore agricultural input subsidy realignment opportunities in the region • Incentivise renewable energy development and off-grid energy storage (also **2.4)** • Evaluate the need for changes in national regulatory frameworks to accommodate green nutrition technologies (e.g., biofertilisers)
2.4 Knowledge base	Identifying and filling in the knowledge gaps that currently constrain the piloting and scaling of green nutrition technologies in the region	• Test & validate core green nutrition technologies in the region • Research to optimize biofertilizer formulations to deliver consistent yields under SSA conditions • Build evidence on the agronomic and environmental benefits of nitrate- versus ammonium-based fertilizers • Identify specific technical constraints (e.g., granulation) and outsource the R&D needed to appropriate partners • Develop materials and implement communications campaigns in the popular press and social media channels on the multiple benefits of green nutrition • Evaluate health and safety issues associated with decentralised green N production
2.5 Transitioning to impact	Identifying financially viable pathways for regional green nutrition development that do not leave some stakeholders behind while safeguarding against the undesirable effects of change	• Explore access to climate finance and low-interest government loans for green nutrition technologies • Explore possibilities for development banks and philanthropic organizations to support pilot projects as well as developing compelling business cases to attract private investment in green fertilizer technologies • Explore and pilot pull incentives such as advance market commitments and auctions and contract-for-differences approaches • Design and implement ICT-based multi-season, multi-stakeholder monitoring using a small set of key indicators • Horizon scanning to monitor technology development and identify potentially game-changing innovations (e.g., white (natural) hydrogen)

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In terms of further development of this analysis, a few steps can be highlighted. First, input from a broader group of food system actors than has been possible so far would be useful to identify gaps and omissions in the analysis. Given the critical importance of political commitment, more input from a range of policy makers in different countries could greatly strengthen the work. Second, an obvious next step is to develop the actions in Table 1 in more detail, such as what needs to be done and when, who may be able to do it, and how it might be funded. These plans could then be integrated into continental and regional initiatives such as the Africa Fertilizer and Soil Health Action Plan [9] and then linked to specific activities on the ground in an appropriate range of pilots. Over time, these plans could become a blueprint for an African-led green nutrition transition in the region that could be used to help guide future work.

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Author contributions

Conceptualization: Philip Thornton, Ana Maria Loboguerrero, Dhanush Dinesh.

Writing – original draft: Philip Thornton, Ana Maria Loboguerrero, Senni Alho, Dhanush Dinesh, Leanne Zeppenfeldt.

Writing – review & editing: Philip Thornton, Ana Maria Loboguerrero, Senni Alho, Bruce Campbell, Dhanush Dinesh, Ulrich Helberg, Jon Hellin, Bruno Partridge, Frank Rasche, Zachary Stewart, Leanne Zeppenfeldt.

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