VoxDevLit

Agricultural Technology in Africa

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Abstract

We discuss recent trends in agricultural productivity in Africa and highlight how technological progress in agriculture has stagnated on the continent. We briefly review the literature that tries to explain this stagnation through the lens of particular constraints to technology adoption. Ultimately, none of these constraints alone can explain these trends. New research highlights pervasive heterogeneity in the gross and net returns to agricultural technologies across Africa. We argue that this heterogeneity makes the adoption process more challenging, limits the scope of many innovations, and contributes to the stagnation in technology use. We conclude with directions for policy and what we feel are still important, unanswered research questions.

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Summary

Although agriculture makes up a large share of employment in Africa, and a larger share of GDP than most other countries, crop yields remain low. There are a number of reasons for this yield gap between Africa and other regions in the world, including farm size and the low utilisation rates of technologies like fertiliser and irrigation. We document these trends in Africa, as compared to other regions in the world, to highlight just how persistent these patterns have been over the last several decades.

This then begs the question of why there has been technological stagnation in agriculture in Africa. The vast literature highlights that there is no single binding constraint for farmers that can explain this stagnation. Instead, it is likely a combination of many constraints, which include credit, liquidity and savings constraints, insurance constraints, knowledge constraints, limited market access, lack of markets for quality, imperfect labour markets, imperfect land markets, externalities and climate change, and heterogeneity. We review the evidence on how each of these constraints matter in African agriculture.

One important recent finding that we highlight in detail is the role of heterogeneity: most technologies are sensitive to local context along multiple dimensions that encompass external environments (for example due to varying nutrients, moisture, soil quality, altitude, temperatures, soil structure, topography, and solar energy) as well as economic conditions (for example, due to heterogeneity in infrastructure and market access). This has far ranging implications for what technologies are profitable where and when, and this may be key to better understanding the technological stagnation.

We highlight what we know to date about heterogeneity in soil and land quality; in weather; and in access to markets. This pervasive heterogeneity has implications not just for sustained technology adoption, but also for the creation of appropriate technologies. Investment rates in technology have remained low in Africa, both on the part of the public sector as well as the private sector. Total spending per farmer on R&D for agriculture in Africa is two orders of magnitude lower than in developed countries. The lack of productive technologies for farmers, given the context they face, and the lack of adaptation of general technologies to this context, is therefore somewhat unsurprising. Added to this is the fact that the cost of inputs like fertiliser still remain extremely high, as these inputs are mostly imported. A focus on reducing these costs (for example via improved infrastructure or encouraging more local production) is one essential path to making these technologies profitable for wider groups of farmers.

We conclude by discussing some open pressing questions in agriculture for Africa. How do we incentivise public and private R&D in the sector, R&D that not just builds new technologies but also customises them to local contexts? Are agricultural productivity improvements the most effective route to eliminating poverty? Can integration of rural and urban markets in Africa provide better incentives to farmers? What are the returns to large scale investments like irrigation? Is there a way to scale down large-scale infrastructure investments? What is the role of the state in agriculture? How will agriculture in Africa adapt to climate change?

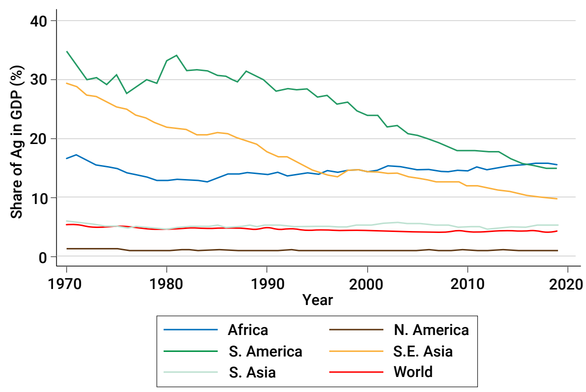
Economic development typically involves a structural transformation in which a dominantly agrarian economy moves towards being more manufacturing and services-based (Timmer 2009). However, across Africa, many countries' economies still rely especially heavily on agriculture compared with the rest of the world, in terms of both output and jobs. The high shares of agriculture in GDP and employment in Africa largely reflect the low level of GDP per capita on the continent (Herrendorf et. al. 2014). Figure 1 shows that agriculture is almost 20% of GDP in Africa[1], compared with a world average of about 5%. Moreover, the agricultural share of GDP for the African region has remained stable over the last 50 years, whereas the share for other regions that started high in 1970 – South East Asia and South Asia – has fallen dramatically. Panel B shows how agricultural shares of employment have declined across different regions of the world over the last 30 years. Africa now has the highest share of employment in agriculture at about 50%, while the world average of employment in agriculture is closer to 30%.

Regions within Africa exhibit considerable variation in shares of GDP and employment in agriculture, the highest being East and West Africa and the lowest Southern Africa. Panel C of Figure 1 shows that agriculture's share of GDP has been falling in East Africa, where it has historically been highest, but not in other regions. Panel D shows the wide disparity in the share of the workforce in agriculture across regions of Africa, although the share is dropping everywhere.

A first step towards structural transformation happens as the agricultural sector evolves from smallholder farmers growing mainly food crops (cereals) for self-consumption to larger-scale farmers growing food crops largely for sale. At present, about 80% of African farmers are smallholders with under two hectares of land, who together account for 40% of cultivated area (Lowder et al. 2016). However, farm sizes seem to have been on the rise in some African countries (Jayne et al. 2016). Increasing agricultural productivity through improved technology is key to this process of agricultural and structural transformation (Bustos et al. 2016, Bustos et al. 2020, Dercon and Gollin 2014, Gollin et al. 2021, Timmer 2009). Examples of specific technological changes that may form part of this process include the mechanisation of farm activities (such as land preparation and transportation), and the use of labour-saving agrochemicals like pesticide and herbicide (Foster and Rosenzweig 2022). There are clearly documented causal links from increased agricultural productivity to reduced poverty (for a good review, see de Janvry and Sadoulet 2010) and improved child nutrition (for example, Glennerster and Suri 2018).

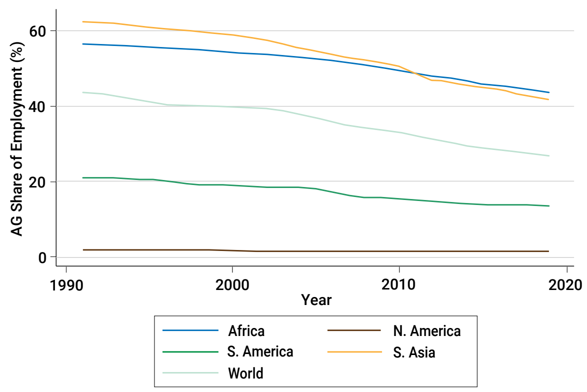
Figure 1: Agriculture's contribution to GDP and jobs

Panel A: Share of agricultural GDP across regions of the world, 1970-2019



Source: United Nations, Food and Agriculture Organization (FAOSTAT).

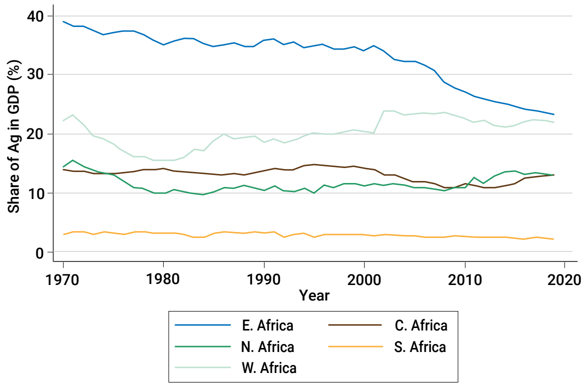
Panel B: Share of agricultural employment across regions of the world, 1991-2019



Source: The World Bank, World Development Indicators (WDI)

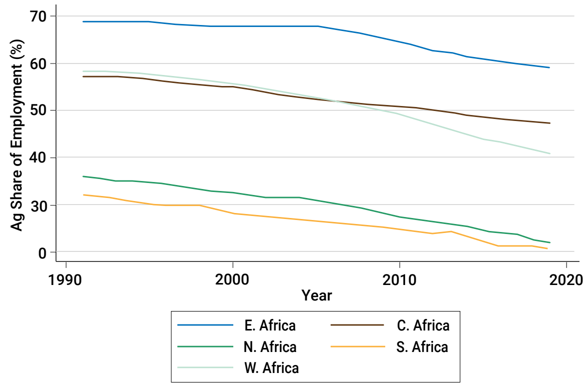
1 The countries that are included in Africa and regions of Africa are described for each of the two main data sources we use (FAOSTAT and the World Development Indicators) in the Appendix

Panel C: Share of agricultural GDP across regions in Africa, 1970-2019



Source: United Nations, Food and Agriculture Organization (FAOSTAT)

Panel D: Share of agricultural employment across regions in Africa, 1991-2019



Source: The World Bank, World Development Indicators (WDI)

Many historical examples demonstrate African farmers' flexibility and openness to innovation: centuries-old examples like the introduction of maize, cassava, and sweet potatoes to Africa as part of the Columbian exchange; decades-old examples, like the transformation of the economy of Ghana or Cote d'Ivoire with the introduction of cocoa (Hill 1963, Chauveau and Leonard 1996); and more recent examples like the emergence of commercial flowers for export from Kenya and Ethiopia - all of which demonstrate a willingness to adapt to farming new crops. There has been some innovation in terms of input intensification on existing cropland, but still, the intensity of fertiliser use, herbicides, mechanisation, etc. lags far behind other regions of the world. Across the world, value-added per worker in agriculture is lower than it is in the rest of the economy, but the gap is largest in Africa (Gollin et al. 2014).

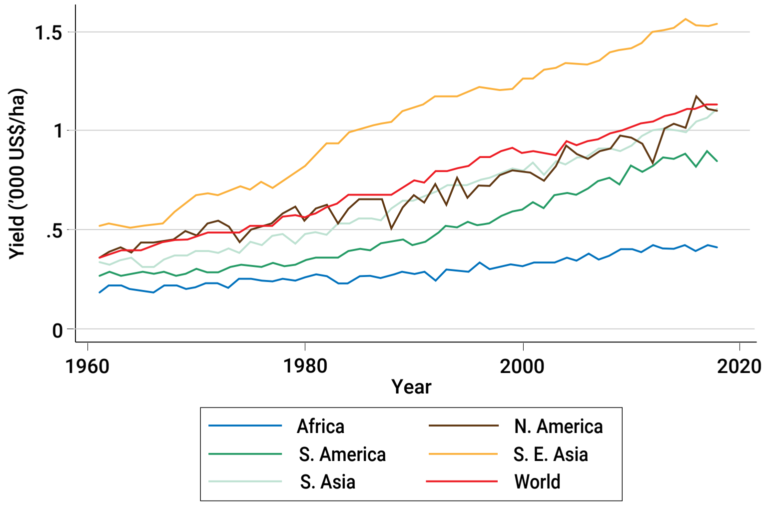
In this VoxDevLit, we start with some background about agricultural productivity and technology adoption in Africa, highlighting how it has lagged. We then discuss what may explain these lags, and what we know about each of these explanations. We discuss the importance of heterogeneity, along a variety of dimensions, in understanding the patterns of agricultural productivity and technology use in Africa. Public and private investment in new agricultural technology in Africa has been extremely limited, and no large set of profitable technologies waits on the shelf to be adopted by Africa's farmers. But there are viable directions for policy, and an important set of unanswered research questions.

The what: Trends in agricultural technology use and productivity in Africa

We first describe some basic patterns of agricultural productivity and innovation in Africa.[2] Figure 2 shows agricultural yields for cereals (as measured in value/hectare) in Africa vs. the world over the last 60 years. Both the level and growth rate of yields in Africa lags behind other regions. Of course, looking at Africa as a whole masks considerable heterogeneity. For example, in more detailed breakdowns from the same data, cereal yields in the Southern Africa region have climbed substantially to $900/hectare in the last decade or so, while yields in countries of West Africa and North Africa rose more modestly to about $500/hectare and yields in Central and East Africa have risen only slightly to about $300/hectare.

2 Much of the aggregate data comes from the Food and Agriculture Organization of the United Nations, which in turn largely relies on ministerial or national statistical office sources. The World Bank's Living Standards Measurement Study--Integrated Surveys on Agriculture programme (Christiaensen and Demery 2017) has provided essential new data on agriculture in Africa, complementing both these official sources and the many smaller-scale researcher-led surveys

Figure 2: Cereal yields ('000 US$/hectare) by region of the world, 1961-2018

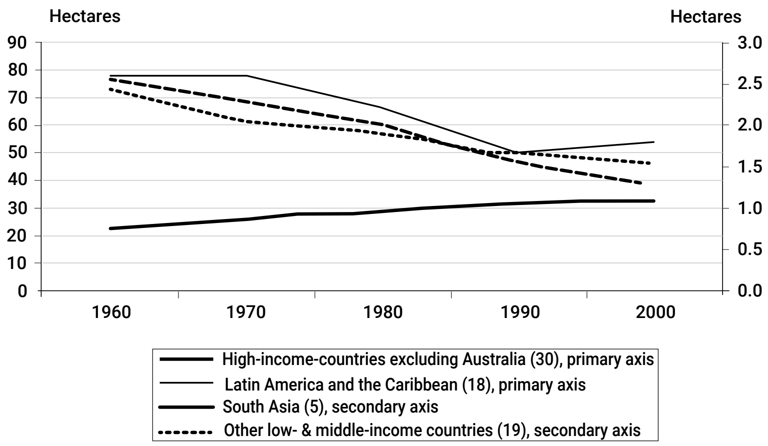


Source: United Nations, Food and Agriculture Organization (FAOSTAT)

Note: Includes Barley, Buckwheat, Canary seed, Cereals nes (canagua/coaihua, quihuicha/Inca wheat, adlay/Job's tears, wild rice, other minor unclassified locally relevant cereals), Fonio, Maize Millet, Oats, Rice (paddy), Rye, Sorghum, Triticale, and Wheat.

These yield gaps may in part be explained by variation in farm size. Figure 3 shows some of this variation, highlighting how the average farm size now is likely not that different in Africa compared to South Asia (though both these regions have dramatically smaller farm sizes than Latin America and the high-income countries). It is worth noting, however, that methodological and definitional differences across countries and time periods mean that data on farm size may be noisier (see Lowder et al. 2016).

Figure 3: Average farm size by region of the world, 1960-2000

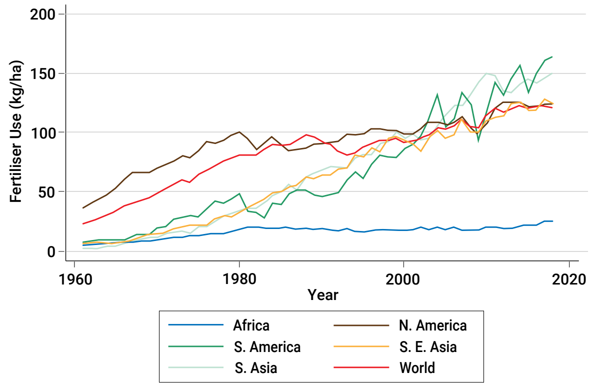


Source: Lowder et al. (2016). Note that Africa is included in "Other low- & middle-income countries".

Yield gaps across the world and across Africa are largely a consequence of the dramatically different technologies being used. Technologies in agriculture involve the biophysical processes of plant and animal growth, coupled with anthropogenic management to create the spatially uniform conditions that distinguish a farm from natural growth. Agricultural technology is embedded in seeds, breeding stock, chemical inputs such as fertiliser, insecticides and pesticides; agronomic practices such as fallowing patterns and plant spacing; and equipment like hand tools, tractors or pumps and other irrigation and water management tools. Use of these technologies varies considerably across regions of the world. For example, Figure 4 Panel A compares fertiliser use in Africa to that in other regions of the world while Panel B compares across regions within Africa. Other regions in the world mostly caught up to North American fertilisation rates at least two decades ago, but Africa still lags far behind. The small increases in fertiliser use on the continent as a whole mask considerable heterogeneity in fertiliser use rates within and among countries (Sheahan and Barrett 2017).

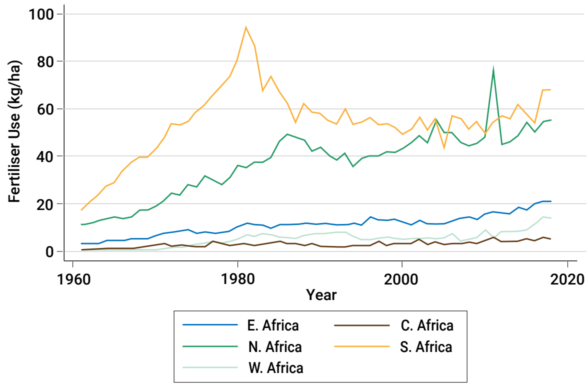
Figure 4: Fertiliser use (Kg/hectare), 1961-2018

Panel A: By region of the world



Source: United Nations, Food and Agriculture Organization (FAOSTAT)

Panel B: Across regions in Africa, 1961-2018



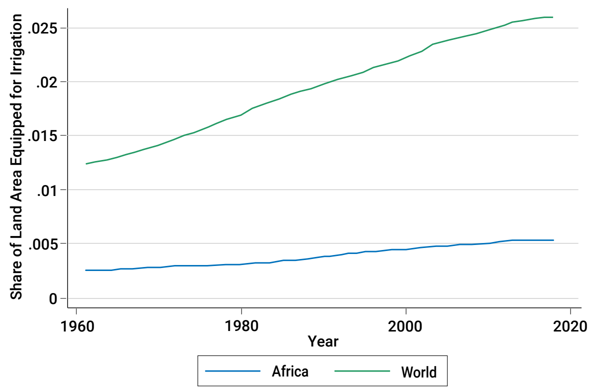
Source: United Nations, Food and Agriculture Organization (FAOSTAT)

Africa also lags far behind other regions of the world in the use of irrigation. Irrigated land is roughly twice as productive, on average globally, as unirrigated land (Fuglie 2008). But as shown in Panel A of Figure 5, the share of agricultural land area equipped for irrigation remains at approximately 0.005 for the continent, compared to over .025 for the world. Again, regions of Africa exhibit substantial heterogeneity: most irrigation is concentrated in North and South Africa (Panel B, Figure 5). Almost all farmers in West, Central and Eastern Africa rely exclusively on rainfall for crop cultivation.

Fertiliser and irrigation are two key agricultural technologies. As we discuss later in the paper, they also reduce heterogeneity in the characteristics of land: for example, irrigation projects partially level out natural differences in farmland's water supply. In turn, the extent of land heterogeneity has implications for how widely other technologies like seed varieties and cultivation practices can be disseminated.

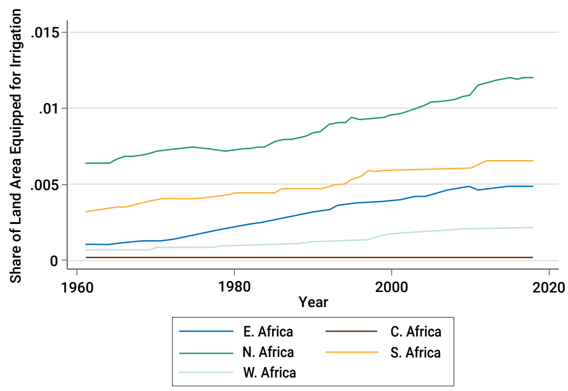
Figure 5: Trends in irrigation, 1960-2020

Panel A: Share of land equipped for irrigation in Africa vs. the rest of the world



Source: United Nations, Food and Agriculture Organization (FAOSTAT)

Panel B: Share of land equipped for irrigation across regions in Africa

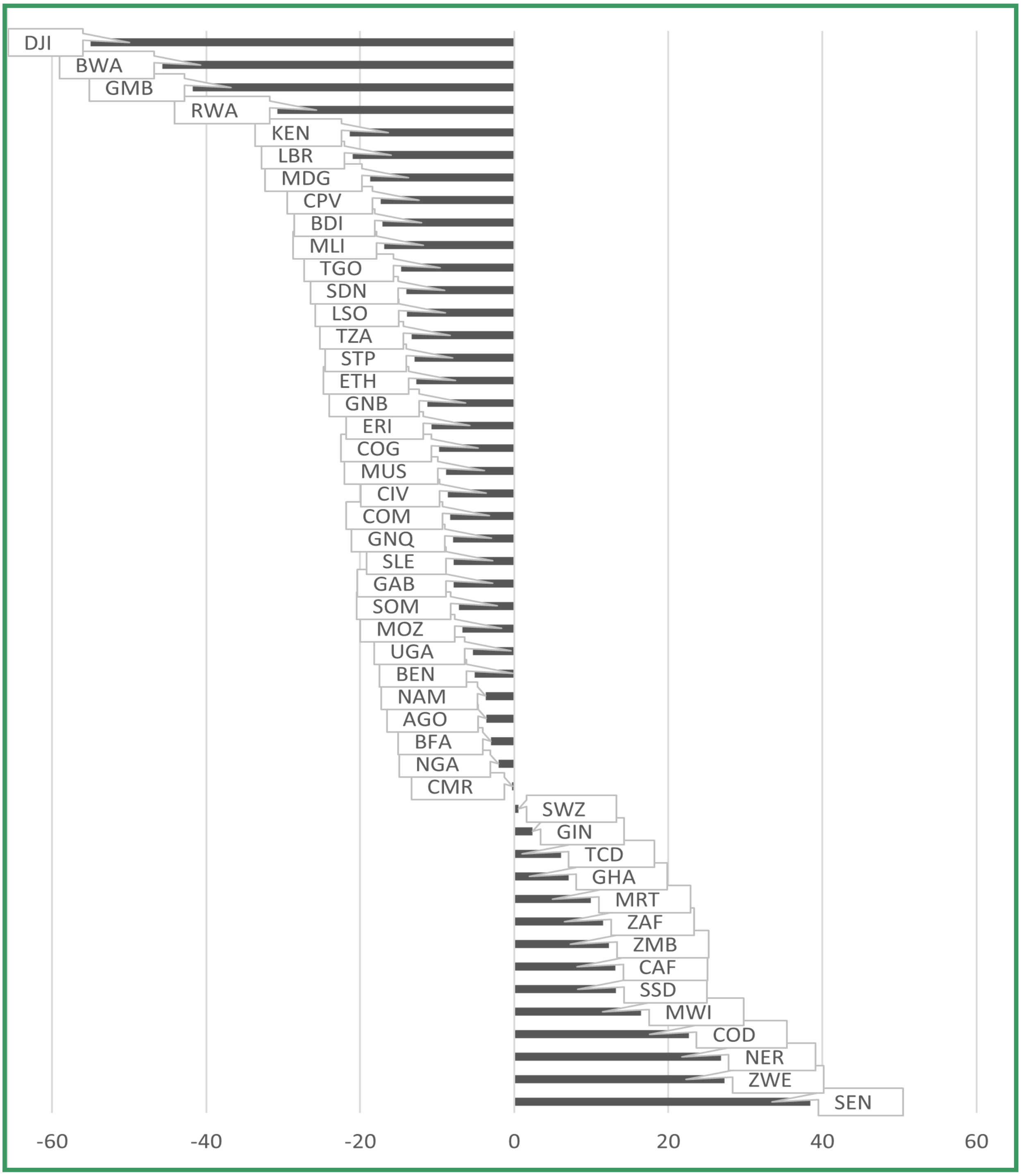


Source: United Nations, Food and Agriculture Organization (FAOSTAT)

Total Factor Productivity estimates reinforce the conclusion that African agriculture has lagged

Total agricultural output growth can arise from extensification through expansion of the agricultural frontier into previously uncultivated lands, intensification through increased use of non-land inputs, productivity growth using existing land and other inputs, or some combination of the three. Over the initial couple of post-colonial decades, most African agricultural output growth arose from extensification. Such resource-driven growth imposes significant environmental externalities and faces intrinsic limits. Expansion of Africa's agricultural frontier has slowed since the 1980s – albeit not in all countries – and the continent remains home to roughly 60% of the world's remaining arable land (Lambin et al. 2013).

Figure 6: Agricultural TFP Growth 2010-11 to 2020-21



Notes: Base year 2015. Created by authors using data from USDA (2023)

As African farmers have intensified agricultural production – i.e. added more non-land inputs like fertiliser, irrigation and labour to the same cultivated area – output and yields have increased, but so have costs of production. While yields grew, agricultural output per worker largely stagnated (Barrett and Upton 2013). That is a basic reason why yields are not an especially good measure of agricultural productivity; they reflect only partial productivity per unit land cultivated. Economists therefore typically prefer total factor productivity (TFP) - roughly speaking, total output value adjusted for the value of all inputs – as a productivity measure. The TFP data reinforce the conclusion that African agriculture has lagged. African agricultural TFP growth to 2010 was only half the rate of the rest of the developing world (Fuglie and Rada 2013). And African agricultural TFP rose only 2% total over the decade since 2010, with only 14 out of 48 countries registering positive agricultural TFP growth from 2010-2021 (Figure 6). TFP growth is the real driver of structural transformation as output per agricultural worker grows, freeing labour to migrate to non-agricultural sectors, and the returns to land and capital rise as well, generating investible capital for non-farm enterprises (Barrett et al. 2017). Indeed, Yeboah and Jayne (2018) show that a strong negative association exists between agricultural TFP growth and the share of employment in agriculture across African countries.

The why: Reasons for Africa's technological stagnation in agriculture

We provide a framework for understanding the range of constraints that account for the stagnation of adoption of productive agricultural technologies in Africa. We highlight some of the more recent studies in African contexts that help us understand why technologies that appear to improve productivity are not developed or adopted. A key source of evidence on the importance of these constraints is provided by the 26 randomised controlled trials (RCTs) across ten African countries supported by the Agricultural Technology Adoption Initiative (Bridle et al. 2019). Broader reviews can also be found in de Janvry et al. (2017), Binswanger-Mkhize and McCalla (2010), Magruder (2018) and Suri and Udry (2021), the last review specifically for the case of Africa. Ultimately, none of these constraints *taken alone* seem sufficient to explain the low levels of technology adoption – and hence low yields – seen in Africa.

Summary: No single binding constraint

No single constraint explains the low productivity in African agriculture; instead, different combinations of constraints seem to bind for different farmers. As a result, packages of technological, policy and institutional interventions – so-called 'socio-technical innovation bundles" (Barrett et al. 2022) – may be the most useful approach to encourage the adoption of new technologies and thus improve agricultural productivity. Current knowledge about effective packages of interventions is limited (we return to this in more detail below), though the literature on this is growing fast.

Examples of packages include a programme in Kenya organised by a non-profit called Drumnet that showed that combining training, agricultural credit, improved access to saving, input supply and marketing assistance led to increased adoption of a novel export crop, french bean (and the related inputs) (Ashraf et al. 2009). Also in Kenya, the One Acre Fund's programme of group lending, crop insurance, regular training, input supply and market facilitation support generated adoption of improved practices, increased use of fertiliser and increased yield and farm profits (Deutschmann et al. 2019). A multi-faceted "economic inclusion" programme in Niger with training, large cash grants, and a set of psycho-social interventions generated substantial increases in improved livestock and the use of fertiliser and phytosanitary inputs (Bossuroy et al. 2022). Mukherjee et al. (2022) find a combination of credit and savings products lead farmers to invest more in farm inputs. Similarly, Deutschmann et al. (2021) find that bundling price premium certainty with training and credit increases adoption of a quality-improving technology in Senegal; Macchiavello and Miquel-Florensa (2019) find that a combination of contractual arrangements resulted in quality upgrading and expanded land under cultivation. Finally, Arouna et al. (2021) test various bundles of contract farming offers, though they find that the simplest option offering just price certainty works just as effectively as versions that bundle price certainty with extension services and/or loans.

All this said, multifaceted programmes are far from a silver bullet. The Drumnet export-promotion programme in Kenya, for example, collapsed after a year when farmers were unable to meet EU production requirements. Other research efforts that have attempted to link buyers with specific quality requirements to smallholder farmers, under the theory that this could stimulate investment in provision of training and input credit, were unable to do so due to farmers' inability to reliably deliver the volume of output required (Hoffmann et al. 2018, Magnan et al. 2021), a challenge inherent in Africa's predominantly rainfed production systems. Some earlier integrated public programmes were costly failures, like the Integrated Rural Development Programmes implemented in the 1970s-1980s (Chambers 2014), and some community-driven rural development programmes had minimal effects (Appiah et al. 2020). Moreover, several approaches to input intensification, while increasing crop yields, generated programme costs that often exceeded the value of additional crop output (Jayne et al. 2018). Could the scarce resources involved have raised agricultural productivity more cost-effectively had they been allocated differently? We still have limited understanding of what programme elements are essential in which environments, and less still regarding the costs of tailoring programmes to these varying environments.

Farmers do show an ability to overcome constraints when the technology is sufficiently productive (i.e. increases productivity enough) and hence actually profitable (Suri 2011). Many examples exist of farmers adopting a technology in particular contexts, such as cocoa in Ghana and Cote d'Ivoire, flowers in Kenya and Ethiopia, improved cassava in Nigeria and rainwater harvesting techniques in Niger. But this notion of "sufficiently productive and profitable" is limited to a geographic, economic and social extent by the heterogeneity that we discuss in the next section.

Below, we summarise some of the overall findings about the main constraints that have been identified and studied in the literature.

Credit, liquidity and savings constraints

Most agricultural technologies come with accompanying costs. If farmers face binding credit constraints and barriers to saving, costs may prevent them from investing in new agricultural technologies. This possibility has motivated a significant amount of research. Much of this work has focused on the adoption of fertiliser and/or improved seeds (which are often complementary inputs). The resulting evidence does not suggest that credit constraints and/or frictions affecting savings can on their own explain the low technology adoption in Africa. Studies on credit and/or savings broadly find increases in adoption, but generally small percentage point increases (though they often amount to large percentage changes relative to the counterfactual). One literature explores factors that may lead to low demand for agricultural credit. Factors include hesitance to list land as collateral, high interest rates, and repayment schedules that do not align well with agricultural cycles (de Janvry and Sadoulet 2020). Abay et al. (2022a) show that rainfall variation, which increases production risk, also reduces the demand for credit. Additionally, the low demand for credit is partly reflective of low demand for the inputs themselves (de Janvry and Sadoulet 2020).

Some authors use capital/cash grants to study whether credit constraints matter for farmers. For example, Karlan et al. (2014) gave farmers in Northern Ghana cash grants and did not find significant increases in adoption or yields for those given cash grants. Beaman et al. (2021) find that cash grants increase both adoption and gross profits for farmers who self-select into a group-lending scheme, but that the average returns to farmers who do not select into borrowing are zero.

We would expect input subsidies to increase input demand if credit and/or liquidity constraints prevent farmers from using improved seed and fertilisers. A number of authors study such schemes (see for example Harou et al. 2022, Matsumoto et al. 2013, Dorward and Chirwa 2011, Ricker-Gilbert et al. 2013, and Carter et al. 2021) using a range of methods to identify causal impacts. Jayne et al. (2018) reviewed nearly 80 studies evaluating input subsidy programmes in Africa, concluding that receiving subsidised inputs raises beneficiary households' grain yields and production levels – at least in the short-term. However, the overall production and welfare effects of subsidy programmes tended to be smaller than expected, for two primary reasons: (1) the subsidy programmes partially crowded out commercial fertiliser demand and hence resulted in less than anticipated increases in total fertiliser use; and (2) the relatively low crop yield response to fertiliser on smallholder-managed fields. Hoffmann and Jones (2021) find that subsidies, combined with training on control of aflatoxin in maize, increase the demand for drying and storage technologies to combat contamination, and that a partial subsidy of a more costly technology is less cost-effective than a full subsidy of a lower-cost technology. Gilligan and Karachiwalla (2023) find that subsidising the full cost of a certified 1kg bag of maize and a 1 litre bottle of herbicide increases the adoption of both inputs. While these papers do find increases in adoption when inputs are subsidised, the estimates vary widely, from quite small to as high as 29 percentage points in Malawi (Carter et al. 2021) - though the subsidy is quite large in this case (a one-time subsidy of US$85, 73% of the cost of fertiliser).

Rather than subsidising technologies directly, some authors have studied subsidising complementary technologies. For example, Aggarwal et al. (2018) study the impacts of providing a limited number of free crop storage devices (PICS bags) and savings accounts on technology use. They find extremely high take up of the PICS bags (see the discussion below on harvest losses) but no change in the use of hybrid seed or fertiliser (though these were already being used at high rates in their sample). Counter to this, Omotilewa et al. (2018) provide farmers in Uganda with free hermetically sealed bags and find an increase in the adoption of hybrid maize that may be more susceptible to pests.

Finally, a set of authors offer farmers credit or savings products directly to study the impacts of these on technology use and yields. Beaman et al. (2023) find strong effects of access to microcredit on input use in Mali. Nakano and Magezi (2020) find small impacts of a loan on fertiliser use amongst those who lacked irrigation, but with no significant improvement in yields in Tanzania. Fink et al. (2020) show that food and cash loans during the lean season in Zambia increase agricultural output and consumption, but via decreases in off farm labour with no impacts on capital inputs or fertiliser use (i.e. the loans do not solve the technology adoption problem). Burke et al. (2019) offer farmers collateralised credit, where the maize harvest is stored by the lender as collateral. This raised farmer revenues and had an impact on the use of storage technology and the timing of sales. When combined with a savings product, this loan also drove greater farm input investment (Mukherjee et al. 2022).[3]

On the savings side, Duflo et al. (2011) find that limited time vouchers at harvest (addressing commitment problems that prevent farmers from saving for fertiliser purchases) raised adoption of fertiliser by 14 percentage points and Brune et al. (2016) find that a commitment savings programme for inputs (that had 20% take up itself), raised the use of agricultural inputs, but only by 13.3 percentage points. In both cases, the absolute magnitude of use of fertiliser or other inputs remained extremely small. Casaburi and Macchiavello (2019) and Brune et al. (2021) find that dairy farmers in Kenya and agricultural workers in Malawi exhibit strong demand for deferred payments, a saving commitment tool for lumpy expenses, such as animal feeds and agricultural inputs.

Overall, constraints on borrowing and saving seem to affect production decisions by many farmers in Africa, but are not the most binding constraints. Alleviating credit constraints does increase the use of agricultural technologies like improved seed and fertiliser, but ultimately by small overall amounts, not by leaps and bounds.

Insurance constraints

Farmers may be unable to insure risk, which may discourage experimentation and bias their investment decisions towards low-risk, low-return technologies. This bias may be exacerbated if they may care more about downside risk, which may be particularly relevant if they are poor (for example, see Kala 2017).

To better understand the role that risk may play in preventing the adoption of profitable technologies, many researchers have studied the adoption and impacts of rainfall-based crop insurance. Largely these studies find (see J-PAL 2016) that the take-up of rainfall insurance at market, or even actuarially fair, rates is very low, likely because existing index insurance products have extremely high basis risk (Carter et al. 2017). Afshar et al. (2021) test two less expensive methods of reducing basis risk - crop simulation models and satellite remote sensing - and find that, compared to crop-cutting estimates (considered best practice), both perform better for the estimation of yield data. Behavioural biases such as loss aversion (Shin et al. 2022) and present bias also appear to limit adoption of these products, which require up-front

3 See also earlier work by Crepon et al. (2015), Karlan et al. (2011) and Tarozzi et al. (2015).

premium payments for delayed payouts (see Casaburi and Willis 2018 and Serfilippi et al. 2020 for two alternative behavioural explanations for this phenomenon).

In circumstances in which production insurance is provided for free, take up has been extremely high, and with generally strong impacts on the use of agricultural technologies. Kramer et al. (2023) find that the willingness to pay for agricultural insurance in Kenya approximates the commercial price of agricultural insurance. Additionally, farmers prefer payments made to their own mobile money accounts rather than to their spouse or ROSCA, indicating that take up, and thus investments made using the credit, also depends on the design of the insurance scheme. Karlan et al. (2014) find that rainfall insurance provision has positive impacts on the use of fertiliser, increasing use by 23.9 percentage points. Similarly, Elabed and Carter (2018) find that free and subsidised index insurance provided to cotton farmers in Mali significantly increased the area planted to cotton as well as the use of fertiliser and improved seed. However, Ahmed et al. (2020) show that, although take up of (freely provided) rainfall insurance was high in Ethiopia, it had no effects on farming outcomes. Once again, there is substantial heterogeneity. Castaing and Gazeaud (2022) aggregate evidence from six experiments and find that index insurance only increases productive investments by 0.06 to 0.12 SD. Moreover, heterogeneity in effects cannot be explained by basic household characteristics.

Some papers have studied the role of crop price risk instead of weather risk. Karlan et al. (2011) show how an agricultural loan product that had an insurance component partially indemnified farmers against low crop prices and impacted their investment decisions. Farmers offered the insurance spent 17.9 percentage points more on agricultural chemicals (mostly fertiliser) than those who had not been offered the product. Consistent with this, Arouna et al. (2021) find that rice farmers in Benin increase their use of seeds, fertiliser, pesticides, and herbicides - and see resulting increases in yields - when offered a fixed-price contract.

What about the inherent risks of the technology? Adong et al. (2020) study a “risk free sample purchase” sales offer where farmers received a small amount of fertiliser, and only repaid this if their harvest increased more than the cost of fertiliser in Uganda. Farmers who repaid were given the opportunity to place a second order with upfront payment and free delivery. The risk-free offer had a take up 73 percentage points higher than a traditional offer, and resulted in a more than 40 percentage point increase in the use of fertiliser.

An important set of technological innovations in agriculture – specifically fertiliser and improved seeds – require upfront investments and generate increased risk for the farmer. Evidence suggests that when this risk can be successfully insured, these risky investments increase, and some of these increases are substantial. However, there remain important challenges in designing low-cost, high quality insurance mechanisms that can serve this role. One option will be to use satellite images, and remote sensing tools to lower these costs, especially as the cost of extremely high-resolution satellite images starts to fall and remote sensing-based crop yield measurement improves (Benami et al. 2021, Lobell et al. 2020). The use of geo-referenced photographs of crop losses also holds promise (Ceballos et al. 2019) and is currently being tested in Kenya (Kramer 2023). On the contractual side, Carter (2022) shows that the sort of loss indexes used for insurance contracts can also be used to trigger lines of credit and as the basis for variable term or commitment savings accounts. Because of the problem of imperfect determination of losses when using remote sensing tools (see the Benami et al. 2021 discussion of “basis risk”), these alternative financial instruments may promise a safer and lower cost agricultural risk management solution for small-scale farmers.

Knowledge constraints

One possible explanation for the low adoption of technologies is that farmers either do not know about new technologies, or they do not have the relevant information about the returns to the technology and how to use it effectively. The literature in this area is vast and includes not just understanding whether providing farmers with information helps, but how best to provide this information, and the role of learning in social networks. A wide variety of studies evaluate extension programmes, public and private. Again, a full review of those is beyond the scope of this piece. But, largely, most of these studies do not find transformational effects on technology adoption (see Caldwell et al. 2019, and Bridle et al. 2019, for good overviews).

In terms of some more recent examples of studies in Africa, Fabregas et al. (2017) evaluate the effectiveness of two different extension approaches on farmers' knowledge, beliefs, and input choices: (i) farmers attend a farmer field day with demonstration plots, and (ii) farmers receive agricultural messages on their mobile phone. The field days increased knowledge but had small effects on input use (at most 4 percentage point increases), the messages did not change input use. Similarly, Kondylis et al. (2017) study a training programme that resulted in small increases in adoption (of 6 percentage points for input use, by 15 percentage points for pit planting and tillage), with no diffusion to other farmers. Bonan et al. (2023) study an extension programme that provided marketing and technology information to farmers in Uganda about new oilseed crops. They show the information provision led farmers to revise their expectations about the yields and prices of these crops. As a result, the adoption of the new oilseed crops increased by 15%. Bernard et al. (2017) show that information on quality increased switching to higher-quality fertiliser by about 25 percentage points. Kondylis et al. (2017) show that training contact farmers who then would train others in Mozambique raises adoption of the technology by the contact farmers themselves, but unfortunately not by other farmers. Horner et al. (2019) find that an agricultural training programme with video messaging increased fertiliser use by 4 percentage points, lime use by 24 percentage points and use of improved seed by 6 percentage points. Maertens et al. (2021) find that farmer demonstration plots had a significant effect on knowledge dissemination and on adoption of planting and management practices, but that farmer farmer field days had no such effect in Malawi. Aker and Jack (2023) find that training on rainwater harvesting techniques significantly increased the extensive and intensive margins of adoption (an increase of over 90 percentage points), and also show that there are spillovers from adoption. The training was similarly effective at increasing adoption when combined with other financial incentives, namely unconditional and conditional cash transfers.

Learning by doing may be more effective than training programmes. "Smart subsidies" that are temporary in nature can encourage experimentation with new technologies, driving increases in usage that persist even once the subsidies are removed, as Carter et al. (2021) find among maize farmers in Mozambique. However, learning by doing may be slowed by inference problems due to heterogeneous returns.

They may also be slowed when the learning is about technologies that only infrequently reveal their benefits, such as stress tolerant seeds or insurance. The Boucher et al. (*forthcoming*) study of a bundle of drought tolerant seeds with index insurance finds that farmers who experienced drought conditions and other yield losses intensified their use of these technologies the year following losses. Predictably, perhaps, those who did not experience the losses walked away from the technology in the next year. While subsidies can indeed encourage experimentation with new technologies (Carter et al. 2021), making those subsidies "smart" for technologies that infrequently reveal their benefits is a rather more difficult problem that would seem to merit further investigation.

Learning by doing can also be impeded by the presence, or beliefs about the presence, of low quality or inauthentic technologies in the market (Michelson et al. 2021, Ashour et al. 2019, Bold et al. 2017). Hoel et al. (2024) caution that learning about quality can be difficult or near impossible if there are incorrect (misattribution of bad luck to poor quality inputs) or uncertain beliefs (ambiguity) about product quality. Looking in particular at how farmers learn, a number of studies document the role of social networks. Pineapple farmers in Ghana use more inputs when their neighbours are surprisingly successful in previous periods (Conley and Udry 2010). Carter et al. (2021) find evidence of increased fertiliser adoption by those in the social network of subsidised farmers. In a framed field experiment in Ghana, Ambler et al. (2023) find that farmers who are provided with a subsidy adopt conservation agriculture in the short and long term, as do those provided with information on long term returns, but not other types of information. Beaman et al. (2021) show that adoption is higher if the intervention targets who to tell about a new technology based on who is central in the social networks in the village. This raises adoption of pit planting, a very specific technology, in Malawi by 30%. Abdulai (2023) documents complementarities between social networks and improved extension services in the adoption of a new wheat variety in Ethiopia. Tjernström (2017) studies the interaction of the usefulness of social networks with variations in soil quality in the village. She finds important social network effects but that these network effects are weaker in villages in which soil quality is more varied, which illustrates how heterogeneity in returns can handicap network effects. We return to heterogeneity in more detail in the next section.

A more nascent literature examines how digitally provided information can increase take-up of agricultural technologies. Van Campenhout et al. (2020) find that farmers in Uganda who watched a video about input use and improved maize practices performed significantly better on a knowledge test than those who did not watch the video, were more likely to use fertiliser and had yields that were 10.5% higher. The addition of IVR messaging, nor SMS messaging, had any impact on these outcomes. Mawunyo Dzanku and Osei (2023) find that voice messages sent to farmers in Mali led to increased adoption of agricultural inputs, the magnitude was not large enough to spur improvements in output or profits.

Fertiliser, improved seed, irrigation, financial products to improve access to credit and insurance, and marketing structures are widely thought to complement one another. Indeed, most hybrid seeds are expressly bred to respond well to inorganic fertiliser application. An enduring puzzle, therefore, is why even among households that do adopt improved inputs, they are often not used synergistically, on the same crop and plot. Sheahan and Barrett (2017) find in LSMS-ISA plot-level data from Ethiopia and Niger, for example, that joint use of multiple fertiliser, improved seed or irrigation inputs occurs on only 13-14% of plots that use at least one of those inputs. This seems to reflect a knowledge gap that might be addressed through extension services. But Africa's extension services are themselves largely in disarray (Jayne et al. 2023).

Overall, it seems that extension and information programmes have limited effects on adoption, except perhaps for the case where the technologies or the crops are truly new. Social networks do matter a lot, especially when thinking about who to target, though many effective interventions are extremely costly to scale and replicate in policy. While most of the literature focuses on farmers' acquisition of technical knowledge, Laajaj and Macours (2021) show that, in a sample of Kenyan farmers, cognitive and noncognitive skills are correlated with yields in a sample of Kenyan farmers.

Limited market access

Lack of market access may deter farmers from adopting new agricultural technologies by increasing the cost of inputs and decreasing the gain from selling outputs. Farmers across the continent face high transaction costs across multiple dimensions: high transportation costs; poor supply chain investments; market power among sellers of inputs and buyers of outputs; and imperfect information about price and quality.

The clearest barriers to market access arise from high transportation costs and poor infrastructure. Atkin and Donaldson (2015) find that the effect of distance on prices of traded goods in Nigeria and Ethiopia is four or five times the effect in the United States. This is consistent with the fact that direct trucking costs in Africa are much larger than those in developed countries (Teravaninthorn and Raballand 2009). Median trade costs in Africa are about five times higher than everywhere else in the world (Porteous 2019).

These costs are likely to deter technology adoption, although there is yet a lot to learn. For example, Aggarwal et al. (2022) study the effects of poor market access in Tanzania on input adoption. They find that doubling transport costs is associated with a reduction in the adoption of fertilisers by 14 percentage points (25%), while reducing travel costs by 50% doubles their adoption (we discuss fertiliser pricing in more detail in section 4). Casaburi et al. (2013) study the impacts of road improvements on agricultural markets in Sierra Leone and find that markets (and hence prices) are better integrated in markets that are closer to improved infrastructure. Dillon and Tommaselli (2022) and Aggarwal et al. (2023) show that input fairs can increase input adoption.

Transaction costs and poor infrastructure can also prevent optimal timing of market access. Improved storage bags have been shown to reduce post-harvest losses and allow optimal timing of crop sales (Aggarwal et al. 2018 and Omotilewa et al. 2018). Burke et al. (2019) show that harvest-time loans can enable providing a vehicle for maize farmers in Kenya to store their crops and sell at times of peak prices. Other recent studies focusing on combinations of credit and storage technologies to delay maize sales include Channa et al. (2022) and Le Cotty et al. (2019). Delavalladde and Godlonton (2023) show that a warrantage in Burkina Faso led farmers to store more grains and pulses, and obtain higher prices by selling over an extended period of time. This idea was also studied by Casaburi et al. (2014) in Sierra Leone for palm oil. Cardell and Michelson (2022) however have shown using 20 years of data from 787 markets in 20 Sub-Saharan African countries that prices fail to rise after harvest approximately 28% of the time and argue that farmers storing to sell later in the year face what is known as “flat price risk”.

Farmers’ market access is typically mediated by intermediaries on both the input and the output side. Evidence on the extent to which these intermediaries increase costs or reduce market integration is mixed (Dillon and Dambro 2017). Some studies find that traders exercise a great deal of market power over farmers’ access to output markets (see Bergquist and Dinerstein 2020, Casaburi et al. 2013 and Newman et al. 2018). An older literature based on analyses of traders’ margins and cross-market price variation (reviewed in Dillon and Dambro 2017) often finds evidence of relatively robust competition in output markets, as do Casaburi and Reed (2022) based on responses to world price shocks and to a randomised subsidy to cocoa traders in Sierra Leone. It seems likely that the mixed evidence reflects a great deal of heterogeneity in the reality on the ground. Less evidence exists regarding the functioning of intermediaries on the input side of the market and few research studies have focused on agri-dealers.

Finally, markets in the region are often not well integrated, either spatially or temporally, in part due to the challenges of gathering information about prices or the availability of buyers and sellers in distant places. This is slowly changing with the growth in cell phone adoption and use, even in Africa (for example, see Aker and Mbiti 2010). Interventions that directly send price information to smallholder farmers via mobile phones have had mixed results (Nakasone et al. 2014, Hildebrant et al. 2023). However, search technologies may be more usefully employed by intermediaries, who operate at the scale required to conduct cross-market trade. Bergquist et al. (2022) find increases in trade flows and reductions in price dispersion from trader take-up of a mobile agricultural marketplace in Ugandan output markets. Although farmers rarely use the mobile marketplace directly, those in surplus areas, where market prices are driven up as a result of the intervention, see increases in revenues. Wiseman (2023) finds a mobile phone application that provides price information and official border costs to traders in Kenya alters traders’ choices of markets and border crossings and affects local market prices. Barrett et al. (2020) provide a useful review of recent work documenting innovations in agricultural value chains linking farmers to food consumers. Institutions such as commodity exchanges likely also have a role to play in reducing frictions in matching supply to demand. The small amount of evidence available on these to-date comes from Ethiopia and Ghana (Nyarko and Pellegrina 2022).

Overall, a lack of market access implies that farmers cannot easily sell their output or easily access inputs, and that the profits from technology use may be low given the current state of infrastructure. There is still much more work to be done in better understanding the role of input and output markets for overall agricultural productivity in Africa. Infrastructure may also interact in important ways with other constraints, as illustrated by some of these studies.

Market for quality

A set of authors has specifically studied the lack of markets for quality, i.e. the lack of different prices for varying quality of crops, in Africa. In theory, adoption of some technologies or techniques may enable farmers to upgrade the quality of their output and earn higher prices and margins. However, if quality price premia are not available to farmers due to challenges with quality measurement, contract enforcement, appropriate storage or transport to maintain quality, or low access to markets with high consumer willingness to pay for quality, then adoption of such technologies will fail to yield benefits.

For example, Prieto et al. (2021) find that Senegalese traders and consumers have both a willingness to pay for drier maize that is safer to consume and some ability to assess moisture content, but that consumers in particular have low confidence in their own ability to assess quality.

There is evidence that farmers have the ability to upgrade quality when given reason to do so, in at least some settings. However, it is less clear whether they are able to do so in response to appropriate price incentives alone, or whether additional knowledge or access to inputs is required. Bernard et al. (2017) study the market for quality of onions in Senegal and find that informing farmers about an upcoming change to the way quality would be assessed in markets raises adoption of quality enhancing inputs by 27 percentage points. Magnan et al. (2021) study whether a price premium for groundnuts in Ghana that comply with aflatoxin regulations changes adoption of the technologies that help deal with aflatoxin. They find that a price premium increases the adoption of recommended post-harvest practices more than training on aflatoxin prevention alone and has a similar impact on aflatoxin contamination as provision of drying equipment. Macchiavello and Miquel-Florensa (2019) find that combining extension and training with a guarantee that a certain fraction of a quality price premium would be paid to farmers (rather than captured by intermediaries), led to substantial quality upgrading of coffee in Colombia, although it is not possible to separate out the role played by different components of the programme. Hoffmann et al. (2023) find that a modest quality premium more than doubled semi-subsistence farmers' adoption of a safety-enhancing input, and that this effect was driven by farmers who were motivated by a combination of health benefits and financial rewards.

One important question is whether farmers do, in fact, face quality price premia, and if not, why not. Bold et al. (2022) find maize farmers in Uganda are able to upgrade quality when offered premium prices for doing so, but that the market offers roughly zero return to quality, though a previous study finds a significant price penalty at farmgate for very low quality (Kadjo et al. 2016). Several studies find returns to observable quality at the retail and wholesale level in informally marketed agricultural produce (Kadjo et al. 2016, Prieto et al. 2021, Hoffmann et al. 2022), and to unobservable food safety in formally processed, branded products, where reputation and regulatory enforcement may play a role (Hoffmann et al 2020). Casaburi and Reed (2022) find that offering quality incentives to cocoa traders in Sierra Leone does improve the quality they supply, although this likely reflects substitution across traders rather than an aggregate increase in the quality supplied by the market as a whole. They find that traders do pass on some of these returns to farmers in the form of more in-kind credit. Macchiavello and Morjaria (2021) investigate the role of competition among coffee mills in Rwanda, and find that an increase in competition between buyers (in an environment with a fairly high average level of competition) actually decreases the quantity and quality of coffee supplied, likely because it undermines relational agreements through which mills provide farmers with access to inputs and loans pre-harvest.

Why quality premia do not exist more often in the absence of experimental interventions is an open question. Hoffmann et al. (2020) suggest that this may in part reflect a lack of both awareness and willingness to pay for third-party verification of food safety on the part of African consumers, in the context of aflatoxin-safe maize flour in Kenya.

Inability to accurately assess quality may be another contributing factor on both the input and the output side, but evidence is mixed. Michelson et al. (2023) review the evidence regarding the quality of non-labour agricultural inputs in Sub-Saharan Africa and show that research has mostly focused on urea fertiliser and glyphosate herbicide. There are disputes over the quality of fertiliser in different countries; Bold et al. (2017) argue that there is significant adulteration of urea fertilisers and herbicides, respectively, in Uganda, but Sanabria et al. (2013), Sanabria et al. (2018a), Sanabria et al. (2018b), Ashour et al. (2019), Hoel et al. (2024), and Michelson et al. (2021) provide evidence that urea fertiliser is of good quality across multiple countries.

While urea fertiliser quality has been shown to be good, glyphosate quality is more variable; insufficient evidence exists regarding other fertilisers, pesticides, and seed. Evidence suggests that farmers believe input quality is low (Ashour et al. 2019, Bold et al. 2017), and that while these beliefs do not always reflect market realities, they inform farmer investment, willingness to pay, and expected returns (Michelson et al. 2021, Gharib et al. 2021, Maertens et al. 2022). Some evidence suggests that farmer uncertainty about input quality may reduce complementary investment in other inputs. Bulte et al. (2014) experimentally vary farmer information about both the quality of the maize seed they are provided (hybrid or open pollinated variety) and farmer uncertainty about the quality type and show that farmers who have more uncertainty about the seed quality reduce labour investment and report relatively lower maize production and yields. Even so, beliefs about input quality respond to information; Michelson et al. (2024) randomise an information campaign about fertiliser quality in Tanzania and find that farmer fertiliser purchases and use increase among farmers in treated marketsheds.

While there is evidence that low-cost changes such as the use of control samples can significantly improve the performance of food safety laboratories (Herrman et al. 2020), the scale, cost, and impact of investments that would be required to meaningfully alter quality assurance capacity and change related incentives is an open question. Digital tools can also play a role – Miehe et al. (2023) test an information clearing house akin to yelp.com and find that exposed farmers are more likely to take up hybrid maize seeds and experience higher levels of productivity. The intervention also resulted in higher trust in certain agro-dealers. Where input quality is low, quality verification schemes can encourage farmers to switch input suppliers, resulting in higher yields (Hsu and Wambugu 2023).

Quality verification can also affect market outcomes. Gilligan et al. (2022) evaluate a government-run certification scheme for hybrid maize, inorganic fertiliser, and glyphosate herbicide in Uganda. Providing information about the new verification scheme to farmers and subsidies for verified products in a subset of markets improved the average quality (and prices) of fertiliser in the treated markets and led to increased adoption of the inputs.

On the output side, Prieto et al. (2021) find that Senegalese traders and consumers have both a willingness to pay for drier maize that is safer to consume and some ability to assess moisture content, but that consumers in particular have low confidence in their own ability to assess quality.

Imperfect labour markets

Only a handful of studies have examined the role that poorly functioning labour markets play in constraining agricultural productivity in Africa, or how best to improve the functioning of these labour markets. One hypothesis for the low use of improved technology and hence low agricultural productivity is that, given the low population density in many African economies and the highly seasonal and often time-sensitive demands for labour in agriculture, labour markets are extremely constrained. Farmers may find it hard to hire or provide the right types of labour at the right times, imposing constraints on their production. Using World Bank LSMS data from five countries, Dillon and Barrett (2017) finds strong evidence of separation failures in agricultural production. This may be partially driven by liquidity constraints (Fink et al. 2020). Jones et al. (2022) show a link between poorly functioning labour markets and limited farm investment, in the context of irrigation investments in Rwanda while Caunedo and Kala (2021) find similar results for mechanisation in India. Carranza et al. (2022) shows that sharing norms may discourage labour supply in the agricultural processing sector in Ivory Coast. There is very little literature here, partly because it is hard to design interventions in labour markets that we think may improve labour allocation and be implementable from a policy perspective.

Imperfect land markets

While there is widespread recognition that land markets are imperfect in sub-Saharan Africa, there has been little work on understanding the ways to improve their functioning and efficiency. Imperfect land markets and poorly defined property rights for farmers may explain part of the low level of investment in agricultural technologies as farmers may not feel confident in their access to the future returns on these investments. For example, Goldstein and Udry (2008) find that the insecurity of property rights is responsible for suboptimal fallowing length, resulting in significantly lower production of crops. A small literature documents the impacts of improvements in property rights on the use of technology, but we still have a lot to learn. Agyei-Holmes et al. (2020) study a pilot land registration programme in Ghana and find that it, in fact, does not affect agricultural investments, but rather releases labour for higher return off-farm uses. Ali et al. (2014) look at a land tenure programme in Rwanda and find the opposite – they find large effects on agricultural investment and on the use of soil conservation practices, especially for female-headed households. Similarly, Wren-Lewis et al. (2020) find that land certification in Benin led to less forest loss, partly because farmers invested more in their existing land, lowering the need to clear land. Finally, Goldstein et al. (2018) study the same certification programme in Benin and find that the programme increased investment, especially by women, who had low tenure rights to begin with. After the programme, women were more likely to leave land fallow, a soil fertility investment.

Despite land abundance in some areas of the continent, land rental has become quite important in some places. Burchardi et al. (2019) cites national census statistics from Uganda that 38% of crop-producing households rent land through sharecropping arrangements. Less formal statistics indicate that 20-25% of Ethiopian farms similarly sharecrop land. As has long been appreciated in economics, the Marshallian disincentives of sharecropping potentially dampen agricultural productivity, despite the advantages sharecropping brings in the form of minimal capital requirements and partial insurance. In an experimental study, Burchardi et al. (2019) show that moving Uganda farmers toward fixed rent contracts resulted in a remarkable 60% productivity increase. Finding ways to create the credit and insurance institutions that would allow a shift to fixed rent contracts would thus seem to be an important, if yet underexplored, way to boost agricultural productivity.

The importance of rural land markets is growing in many countries of Sub-Saharan Africa (Deininger et al. 2017, Jayne et al. 2021). While large-scale transactions receive the largest attention in policy debates, most transactions occur among small or medium farmers (Jayne et al. 2016). Nevertheless, a growing of body of work suggests that land market imperfections inhibit the growth of particularly productive farms (Restuccia and Santaeulàlia-Llopis 2017); preclude farmers from capturing potential returns to scale associated with mechanisation (Foster and Rosenzweig 2022); and slow the development of robust value chains that can support technological innovation (Barrett et al. 2020). Market imperfections in rural land markets can include social norms; in Malawi, Krah et al. (2024) show that field characteristics including soil quality explain less than a third of land rental rates and find that villages with stronger experimentally-elicited fairness norms have tighter ranges in rental rates. Rental rates are likely to be capped in villages with stronger fairness norms and may serve to protect tenants from rent increases.

Acampora et al. (2022) use an RCT in Western Kenya to subsidise land rentals and find that this improves equity and increases output and value added on the rented plot. They highlight how land market imperfections matter and how these interact with labour market frictions. Customary land tenure systems inhibit the commercialisation of land, but they provide guarantees of some access to land for most people in rural Africa and play a central role in informal social protection. Transformation of land tenure systems to facilitate agricultural innovation requires attention to these broader consequences for the distribution of power and welfare in rural communities.

Perhaps because of these limitations in the land tenure system, a number of countries (particularly Ethiopia, Nigeria, Mozambique and Sudan) began facilitating large-scale land acquisitions by outside investors. Deininger et al. (2011) calculate that as many as 40 million hectares had been transferred under these schemes, with a median project size in the thousands of hectares. While often controversial, these programmes were justified in terms of the productivity gains imagined to occur directly through large-scale farming, and with the spillovers from the large-scale to smaller-scale farms (Collier and Venables 2012). As summarised by Deininger and Goyal (2023), there is at best modest evidence that these large-scale land transfers have succeeded in generating productivity gains and spillovers.

It is worth noting that properly functioning rental markets for agricultural equipment could enable smaller farms to overcome scale-related barriers. However, barriers in the rental market often preclude this (Dillon and Barrett 2017, Sheahan and Barrett 2017, Caunedo and Kala 2021, Daum 2021). There is a need for more research in this space.

Externalities, land and climate change

A large and growing literature documents the negative impacts of climate change on agricultural productivity across the world, especially in Africa (Ortiz-Bobea et al. 2021, Barrett et al. 2023). We do not review that literature here given our focus on agricultural technologies in Africa. Instead, we focus on the diffusion of technologies and strategies that help farmers deal with these impacts of climate change.

A significant portion of African farmland has one or more of the following conditions that reduce crop response to fertilisers and other inputs: acidic soils, low soil organic carbon, sandy soils, and micronutrient deficiencies. Until these soil issues are somehow addressed, input intensification may be limited (Sanchez 2019). However, the adoption of a wide variety of natural resource management practices remains very low in Africa (see Stevenson and Vlek (2018) for case studies on Zimbabwe, Zambia, Malawi, Niger, Mozambique, Kenya and Rwanda). Much of the existing work tries to incentivise adoption of these practices in a variety of ways. For example, Jayachandran et al. (2017) provide incentives to forest-owning households to conserve their forests in Uganda and find that these incentives do reduce deforestation without creating additional deforestation elsewhere. Oliva et al. (2020) study subsidies for the take up of agroforestry (trees that improve soil fertility over the long term) in Zambia. Much as the subsidies do increase take up, the follow through to future investments in the trees is low and uncorrelated with the initial subsidy (the follow through seems to require additional incentives). Coppock et al. (2022) study the effects of a community-based rangeland and cattle management programme in Namibia, which was successful in improving community resource management but had no effects on cattle productivity or incomes. Aker and Jack (2023) find training farmers in Niger on an agricultural technique that helps reduce land degradation and restore soil fertility increased adoption by over 90 percentage points, while adding conditional or unconditional cash transfers had no additional effect. Jagnani et al. (2021) find that Kenyan maize farmers respond to changes in pest ecology induced by rising temperatures by increasing pesticide use, which necessitates reducing fertiliser application given binding budget constraints.

The where and when: The broader role of heterogeneity

Many agricultural technologies are extremely sensitive to local circumstances: nutrients, moisture, soil quality, altitude, temperatures, soil structure, topography and solar energy are all required in appropriate proportions and timing for crops and animal husbandry, and farmers face different threats from diseases and pests (Evenson and Westphal 1995, Moscona and Sastry 2022). Overlaid on these natural conditions is heterogeneity in infrastructure and market access, and hence in the prices of inputs and outputs, again both over time and space. Even in agricultural regions outside Africa with well-developed agricultural technology use we see fine geographical variation in optimal technology choices: in the American state of Illinois, for example, optimal maize varieties differ at the scale of a few dozen miles (for example, see https://burrusseed.com/product-selection-guide/).

There could be several implications of this heterogeneity. One, of course, is that some technologies may simply not be profitable everywhere. But there are additional implications: e.g. it might be hard to learn from one's neighbours if they have different conditions to your own, and there might be limited incentives for R&D of technologies if they have small markets and are only relevant for a small segment of the population. For example, evidence suggests that many agricultural technologies are developed by and most appropriate for high-income countries. This mismatch limits the transfer of technologies to low-income countries that have different pests and pathogens and reduces global crop production (Moscona and Sastry 2022).

Heterogeneity may be key to understanding technological stagnation in African agriculture more broadly. For Kenya, Suri (2011) shows large heterogeneity in both gross and net returns to hybrid seed and fertiliser. Indeed, the extent of heterogeneity appears to be far larger in sub-Saharan Africa than in temperate regions. Claassen and Just (2011) study the variance of log yield across farms in the United States: they find that the 95th percentile of corn yield is 190% larger than the 5th percentile yield. For comparison, the 95-5 ratio for

Uganda is 9,304% and for Tanzania 2,558% (Gollin and Udry 2021). A substantial share of this variation is likely due to heterogeneity in soil, moisture, temperature and other dimensions of growing conditions over space. But the heterogeneity is not fully exogenous: some technologies might reduce this heterogeneity – e.g. irrigation lowers the degree to which yields vary with rainfall. The exceptional degree of heterogeneity in Africa is at least in part a consequence of the 18th to 20th century history of low population density on most of the continent (itself caused in part by the slave trade and associated violence and political disruptions as discussed in Manning (2014)). The low population density increases infrastructure costs, so that farmers rely on rainfall for irrigation and on periodic fallowing (rather than fertiliser) to maintain soil fertility (Boserup 1965). Agricultural production therefore is more tightly connected to local conditions such as rainfall realisations, plot-level availability of soil nutrients and the existence (or not) of a nearby road and/or market. The implications of such heterogeneity can be far reaching, not just in explaining the lack of adoption, but also in underscoring the challenges of developing new agricultural technologies and designing policy that ultimately improves yields.

Soil and land quality

The nutrient composition, physical properties and biochemistry of the soil affects the profitability of any given seed, fertiliser or other chemical input, or other agronomic practice. Sanchez (2019) provides a comprehensive review of soil properties and soil management across the world, highlighting the extreme heterogeneity in soil quality and the importance of the interaction of nutrients and water availability. For example, the maize yield response to fertiliser is strongly dependent on sandiness and on soil carbon content and thus farmers' use of fertiliser responds directly to soil conditions (Marenya and Barrett 2009a, 2009b, Burke et al. 2020). These land characteristics vary in important ways across communities, at scales as small as hundreds of metres – Hengl et al. (2021) show maps of data collected by the International Soil Reference and Information Centre (ISRIC), displaying differences in the acidity of soil at a resolution of 30 metres. Researchers have shown and farmers have described substantial variation in soil characteristics *within* farms, and farmers adjust production decisions to accommodate that variation (for example, Tjernström et al. 2015). Soil quality is not fixed, but evolves over time in response to farmer actions, weather shocks and environmental influences including seed dispersal, erosion, rainfall, and the movement of pests.

Given large variations in soil quality across even small geographic areas, optimal technology choices will vary between plots or even on a specific plot over time. For example, Harou et al. (2022) show that in rural Tanzania, within-village variation accounts for almost one-third of overall variation across the district in several key soil nutrients, and that recommended amounts and types of fertiliser vary significantly within villages. Farmers who were provided with plot-specific recommendations for appropriate fertiliser use (along with vouchers for reduced cost access to inputs) were more likely to apply the recommended fertiliser, and increased yields by over 150% relative to the control group. This work highlights both spatial variation in soil characteristics (lots of variation within villages) and faulty information. Government recommendations do not address sulphur and about 95% of plots in the entire sample are sulphur-deficient; farmers that receive the information plus the vouchers address the sulphur deficiency but they do not act on the more nuanced, plot-specific limitations that vary within villages. Abay et al. (2022b) show that farmers in Ethiopia do not apply the correct types or amounts of fertiliser that their plots require, lowering yields and partially explaining the heterogeneity in returns to fertiliser. Additionally, Kurdi et al. (2020) find that incentives can be perverse - a fertiliser subsidy for nitrogen fertilisers in Egypt led to the overapplication of nitrogen fertiliser, which could then adversely affect soil, water, and environmental health. Berazneva et al. (2023) experimentally test the relationship between within-village soil heterogeneity and farmer investment in soil testing across villages in Malawi. The experiment randomly varies the plot to be tested across village residents and shows that farmers contribute more to the testing of plots that they perceive as similar to their own. Free riding occurs when more farmers in a village have soils of the same type.

Heterogeneity in weather

The returns to investment in cultivation in sub-Saharan Africa (and South Asia) can vary widely, depending upon the local weather (Rosenzweig and Udry 2020). As a recent example, McCullough et al. (2018) use an experimental crop trial meta-database to show that the profitability of adopting fertiliser varies strongly with weather outcomes. This temporal heterogeneity makes the adoption decisions of farmers much more difficult; it also demands a longer-term perspective for those who seek to understand these adoption decisions.

There has been some investment to develop and disseminate crop varieties that are more resistant to poor weather realisations, and in particular to varieties that may outperform the alternatives during poor weather realisations. This is an exciting area of varietal improvement, though such varieties are still few and far between. Examples of such varieties are Swarna Sub-1 flood resistant rice in India (Emerick et al. 2016) and drought resistant maize (Boucher et al. *forthcoming*).

Heterogeneity in access to markets

Scarce and low-quality road infrastructure, together with imperfect competition in transportation, similarly generate large variation across space in both input and output prices. These high transportation costs interact with a spatially dispersed population of farmers to produce markets for agricultural output and inputs that are far from a perfectly competitive benchmark (Bergquist and Dinerstein 2020), limiting technology adoption and farm productivity (Aggarwal et al. 2022, Minten et al. 2013). The traders to whom farmers sell (often at farm gate) are not competitive, further affecting output prices (for example, Casaburi et al. 2013). The consequent price mark-ups also vary across space. Some countries have a policy of uniform national prices of some inputs; such policies are problematic given high transportation costs because they can lead to considerable spatial variation in access to these inputs and hence in their returns and adoption, as Suri (2011) shows for Kenya.

These high, heterogeneous, and variable trade costs interact with the adoption of new technologies in specific ways; for example, subsidies for fertiliser only raise farmer incomes when trade costs are low (Porteous 2020). Kumar et al. (2023) also show that costs for adopting technologies, even with the provision of subsidies, is more expensive for rural farmers who need to travel and may need to buy from specific retailers. They examine the Malawi Farm Input Subsidy Programme (FISP) and find that the subsidy reduces the spatial cost gradient but does not eliminate it.

Pervasive heterogeneity and technology adoption

This pervasive spatial and temporal heterogeneity presents challenges, both for African farmers attempting to make optimal technology decisions and for researchers seeking to understand farmers' technological choices. A technology that is profitable on one set of farms in a particular year may fail on other nearby farms or in other seasons, limiting the extent of learning and the duration needed for learning about benefits to be sufficient to induce adoption.

Agricultural technologies vary in the degree and nature of their sensitivity to local circumstances. The profitability of adopting mechanical field preparation in savannah regions (that is, a grassland with numerous but widely spaced trees), for example, depends on factor prices and topography, but not as strongly on local variations in soil characteristics. The profitability of adopting improved storage technologies depends on prices and local insect populations, but not as much on topography. Innovations tied more closely to the biological and physical characteristics of a plot, like chemical inputs and seed varieties, exhibit the most heterogeneity in returns (for example, Harou et al. 2022).

Farmers presented with an opportunity to adopt a new agricultural technology must translate information they receive regarding the performance of the technology in specific circumstances to its likely performance on their own farms. Understanding how farmers make this translation remains incomplete. Information from extension agents and expert advice can be effective, but some farmers place more weight in learning from others who are more like themselves (for example, Munshi 2004, BenYishay et al. 2019).

Heterogeneity has implications for the optimal supply of agricultural innovations as well, because the circumstantial sensitivity of many innovations limits the extent of their potential impact, reducing the incentives for private research. Heterogeneity can also make it costly and complex to scale extension or for agri-dealers to stock an appropriate range of locally-relevant technologies. In addition, any cost-benefit analysis for public support of research into new agricultural technologies needs to take the more restricted impact into account.

The RCT results reported in Bird et al. (2022) show that improved maize varieties locally adapted for a small, "niche," agro-ecology in Kenya's mid-altitude zone indeed offer substantial yield and economic gains above and beyond those offered by hybrids bred for broader market segments. These authors argue that this lack of adaptive local breeding likely explains the very low uptake of improved seeds in this agro-ecological niche (25% in the mid-altitude region versus 80% in Kenya's larger agro-ecological regions). They also argue that the cost-structure of large seed breeders and the capital constraints of local seed companies present an organisational challenge to the successful creation of varieties of Africa's many heterogeneous zones.

The how: Where to from here?

Given what we know to date about the stagnation of both agricultural technology use and agricultural productivity in Africa, what policy actions might be appropriate?

Investments in technology for agriculture

There is a need for more and longer-term investments in research and development for agricultural technologies themselves in Africa. Total spending per farmer on R&D for agriculture in Africa is two orders of magnitude lower than in developed countries. The United Nations Food and Agriculture Organization, based on data from ASTI (IFPRI), estimates that spending per farmer on R&D across Africa has been about $50 (in US dollars at purchasing power parity) or less since 1990.[4] For comparison, R&D spending per farmer in Brazil was about $1200 in 2000 and has more than doubled since then.

Across regions of Africa, one can see substantial increases in Southern Africa and East Africa, where R&D spending per farmer has recently climbed substantially to nearly $250 and almost $150, respectively. But these changes make the average R&D spending per farmer for Central, North, and West Africa, hovering at less than $25, look even lower. Countries like Uganda, Zimbabwe, Niger, Burundi, and Ethiopia had growth in public agricultural R&D spending at annual rates of 6% or more from 2000-2014, according to data from CGIAR ASTI. Conversely, countries like Togo, Gabon, and Guinea averaged annual declines of 4% or more in public agricultural R&D spending over that time frame.

In short, the lack of productive new agricultural technologies ready to be adopted in Africa is no mystery; it is the result of low levels of agricultural R&D investment in the past.[5] In addition, volatility in already low levels of investments make the problem worse. Rawat (2020) shows for public investment in R&D, the volatility in these expenditures is highest in sub-Saharan Africa (and lowest in South Asia).

4 This estimate for Africa includes only a sub-sample of countries where there is consistent data during the last three decades: Benin, Botswana, Burkina Faso, Burundi, Republic of Congo, Côte d'Ivoire, Ethiopia, Gabon, The Gambia, Ghana, Guinea, Kenya, Madagascar, Malawi, Mali, Mauritius, Niger, Nigeria, Senegal, South Africa, Sudan, Togo, and Zambia.

5 Perhaps surprisingly, the share of government expenditure that goes to agriculture in Africa is similar to other world regions, according to FAOSTAT data. The expenditure on agriculture includes agricultural research and extension services, input subsidies, irrigation, marketing and rural road infrastructure. Across Africa, about 5% of all government expenditures go to agriculture, whereas for the world as a whole, as well as comparable regions like South East Asia, only about 3.5% of government spending goes to agriculture as defined here.

Figure 7: Public and private agricultural R&D spending by region, 2011 (US$M PPP)

						EMEA		APAC	
Sector	High-Income countries	Other Countries	World	North America	Latin America	High-Income Countries	Other countries	High-Income countries	Other countries
Public agricultural R&D	18,212	24,116	42,328	5,501	6,901	7,879	2,999	4,832	14,215
Private agricultural R&D, allocated to country of company incorporation	12,326	1,933	14,260	6,458	36	5,023	110	845	1,788
Private agricultural R&D, allocated to location of company product sales	9,510	4,750	14,260	5,106	1,968	3,696		3,489	

Note: EMEA refers to Europe, Middle East, and Africa; APAC refers to the Asia Pacific region

Source: Heisey and Fuglie (2018).

Although private R&D in agriculture has grown tremendously over the last 20-odd years and is expected to play a stronger role in the future (Fuglie 2016), it still comprises only a quarter of overall agricultural R&D. Moreover, almost all private agricultural R&D is in (and for) the developed world, as illustrated in Figure 7 below (Heisey and Fuglie 2018).

Agricultural research and development is a process that builds on itself. For example, in South Asia after the introduction of the initial “green revolution” varieties of rice, Evenson and Gollin (2003) show that a sustained R&D effort lead to multiple generations of new varieties characterised by gradually increased yields, improved agronomic performance and nutritional content, and increased resistance to pests. In India, 20-40 new varieties of rice have commonly been released annually since 1970, along with 10-20 new varieties of both maize and wheat, as reported by the Indian Council of Agricultural Research (ICAR) - Indian Institute of Maize Research (IIMR). In addition, the numbers of new varieties introduced has risen in recent years (as shown in SeedNet India Portal). In contrast, in Kenya where maize is the main staple, it was common to have five or fewer new varieties introduced annually from 1970 to 2000, although since then the number of new varieties of maize being introduced has risen to Indian levels, according to data from the Kenya Plant Health Inspectorate Service (KEPHIS). Of course, what matters is not just the number of varieties but the quality or yield improvement provided by these varieties. As Karanja (1996) highlights for the earlier research and development efforts in Kenya, research yields were exhibiting a “plateau effect”, with newly released varieties in 1989 having smaller yield advantages over their predecessors than previously released ones. However, Bird et al. (2022) show that locally-adapted maize varieties have important yield and revenue effects in Kenya, both for wealthier and poorer farmers. In addition, much of Africa relies on staples other than rice, wheat, or maize. Internationally-funded research in other staples such as millet, sorghum, or cassava began decades later, in the 1980s rather than the 1960s. Present-day yield gains from HYVs in roots, tubers, and pulses have been a fraction of those in cereals, aligning with the additional decades of R&D benefiting cereals (Gollin et al. 2021).

Broad or customisable technology

The substantial heterogeneity experienced by most African farmers can be addressed in two ways. One approach is that a combination of irrigation, permanent cultivation, and terrain engineering can reduce local differences. The other is to seek new technologies that are more customisable or that can be profitable across a wider range of circumstances.

In developed countries, there is much more customisation of new agricultural technologies to very local circumstances than there is in Africa. More than 60 years ago, Griliches (1957) was showing how new technologies were adapted to local conditions in US agriculture. It has long been common for farmers in developed country agriculture who are separated by only a few dozen miles and facing almost uniform input and output prices to prefer different seed varieties for major grains. Hurley et al. (2004) show within single farm plots in the American state of Minnesota, optimal fertiliser doses can vary by a factor of two. Recently, this customisation of technology to (relatively) small variations in growing conditions, even within a single plot, has intensified in high-income countries with the growth of precision agriculture (for example, Stoorvogel et al. 2015, Schimmelpfennig 2016, North Dakota State University undated).

Agricultural research efforts in most of Africa have been less successful in adapting technology to local variation. In most of Africa, only extremely limited customisation of modern varieties of seed is available. In agronomic trials in northern Ghana, for example, the best performing maize seed was a variety developed for South African conditions (van Asselt et al. 2020). Fertiliser recommendations to African farmers are often uniform over large areas of highly variable soils (Michelson et al. 2021). Scale economies must be important here. Small and spread-out farms make sending out different extension agents with different messages costly.

Developing, testing, and adopting new technologies in this environment poses significant challenges. Customisation requires much better feedback from a much larger and more diverse set of farmers. One promising direction is greatly expanded use of farmer participatory trials to map heterogeneity and optimise recommendations. A related approach would use the rapid expansion of information network availability across Africa to carry out on-farm trials of new technologies at a much larger scale than has been possible in the past (Newman et al. 2012). For example, Precision Development (PxD) is building low-cost information systems to reach smallholder farmers with personalised advice through their mobile phones (Cole and Fernando 2021) and now reaches over 5.7 million farmers in ten countries. Cole and Fernando (2021) find that farmers are willing to pay $2 for a nine-month subscription to the service, which could be a viable business model if it is expanded. A first step in harnessing these opportunities is building up the base of relevant local information regarding what technologies are viable for testing in what local areas of each country.

One obstacle to this approach is the low number of agricultural research stations and the historically low numbers of staff and high turnover at these stations (Lipton 1988) across countries in Africa. The United States has 607 research stations (Pearson and Atucha 2015); based on data on farmers from USDA (2021), this constitutes about 134 research stations per 100,000 farmers. For comparison, we looked at data on the number of research stations in some African countries from Beye (2002) along with data on farmers from about 2002 from the Agricultural Science and Technology Indicators (ASTI) published by CGIAR. Ghana has only 14 agricultural research stations (0.28 per 100,000 farmers); Malawi only 154 (0.34 per 100,000 farmers); Mali has seven (1.02 per 100,000 farmers); Madagascar has 24 (0.42 per 100,000 farmers); Kenya has 25 (0.22 per 100,000 farmers); Cameroon has 30 (0.79 per 100,000 farmers); and Senegal has 30 (0.94 per 100,000 farmers). Tests of new varieties by the existing network of African research stations cannot provide the necessary local information on returns to varieties that farmers need, which in turn can help to explain the large differences in returns between station trials and on-farm trials that are often observed (Laajaj et al. 2020).

We also do not know enough about what seed varieties are actually used by African farmers. Recent work on DNA fingerprinting finds discrepancies between self-reports of what farmers say they are using and the DNA results (Wossen et al. 2019a, 2019b, Poets et al. 2020). Clearly, we need a significant investment push to generate fine-scale information on what technologies are used and the returns to those technologies.

In that vein, large-scale participatory trials of new technologies could provide a foundation for a broader process of integrating “citizen science” into agricultural R&D and extension. As discussed earlier, the same information technology that would permit the communication of trial protocols and results between scientists and participants is already being used to provide inexpensive, timely information and advice to farmers. It could also provide a forum for generating new ideas for trials and for crowd-sourcing farmer input into research investment decisions (for example, Cole and Fernando 2021). Inducing increased private investment into agricultural technologies appropriate for small farmers requires new policy instruments (Barrett 2023).

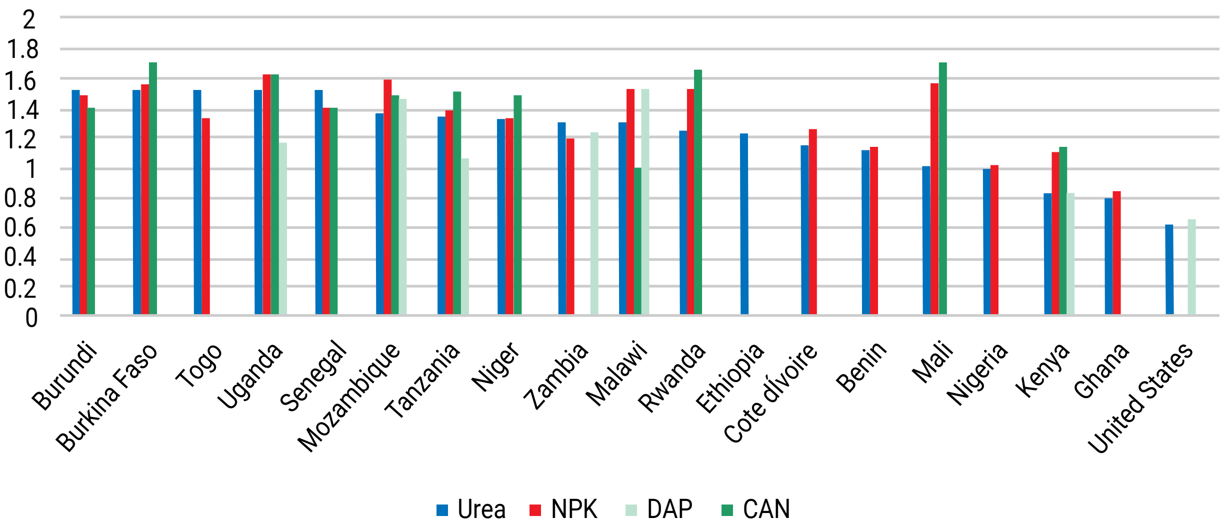
Cheaper inputs

Many African farmers face extremely high fertiliser prices. Over 60% of the fertiliser in Africa was imported in 2016 (see the Africa Fertiliser Market Development Report 2018) and this, along with extremely high transport costs and low population density on the continent, implies many farmers often face high fertiliser prices, which makes fertiliser unprofitable for them as a technology. For example, fertiliser prices in some African countries (see Cedrez et al. 2020) can be twice as high as in the US (see Figure 8). Additionally, major shocks such as the Russian invasion of Ukraine, which caused fertiliser prices to more than double, can make the price of fertiliser volatile (Glauber and Debucquet 2023).

Policy can try to target these costs indirectly in a multitude of ways. First, investing in infrastructure that will lower transports costs not only lowers the prices of inputs but also potentially improved market access for outputs, as lower costs of search and trading lead to improved market integration (Casaburi et al. 2013, Newman et al. 2018, Bergquist et al. 2022). Another alternative would be to encourage more local production of fertiliser or more geographically local trade in fertiliser. As of January 2021, there were only 135 fertiliser plants across all of sub-Saharan Africa (excluding South Africa): 17 are manufacturing plants and 101 are processing plants (IFDC 2021). In some countries, the prices of fertiliser may be high because a small number of importers dominate the market. In these cases, some combination of short-term assistance to entrants or pro-competitive policy interventions may be needed.

Policy can additionally try to target these costs directly in a multitude of ways. One obvious approach would be to subsidise fertiliser, but it is not clear that such subsidies are beneficial in the long term or are a sustainable policy tool to increase adoption and yields (see earlier discussion). In addition, long-term subsidies on nitrogen-based fertilisers have sometimes led to systematic (and potentially serious) overuse and, hence, longer term soil fertility issues, as Kishore et al. (2021) document in Bangladesh, India, Nepal and Sri Lanka.

Figure 8: Fertiliser prices (USD/kg) across countries in Africa and the US (2016)



Source: Cedrez et al. (2020) for Africa; USDA ERS for the US

An alternative would be to encourage more local production of fertiliser or more geographically local trade in fertiliser. In some countries, the prices of fertiliser may be high because a small number of importers dominate the market, making it not very competitive. In these cases, some combination of short-term assistance to entrants or pro-competitive policy interventions may be needed.

Supporting other inputs may be useful as well. The earlier discussion noted that although rainfall insurance affects the use of technology, farmers are still largely not willing to pay for it at actuarially fair prices (J-PAL 2016). Subsidies for such insurance could become one of the basic social welfare tools for these economies. Investments in improved weather forecasting could also reduce weather risks more directly. Yegbemey et al. (2023) experimentally evaluate weather forecast services in Benin and show positive effects on labour productivity in maize (but not in cotton).

Conclusion: Pressing questions

When it comes to improving agricultural technology and productivity in Africa, we have learned much about what doesn't work. While this is valuable, it also makes apparent how much we do not know. We conclude with seven pressing questions to guide future work.

First, how should we provide incentives to either the public or the private sector for the development of new agricultural technologies that are locally customised and how should we provide incentives for experimentation with these technologies? Rao et al. (2019) estimate the returns to agricultural R&D and show that they remain as high as ever (their median estimated internal rate of return is over 40% per year, with no significant time trend). Barrett (2023) proposes "benevolent patent extensions" as a way to induce private sector investment in otherwise-unprofitable R&D to address the challenges faced uniquely by smallholder farmers.

Second, are improvements in agricultural technology and productivity the most useful way to raise the standard of living and create a path out of poverty, or should the focus be on investments in the non-agricultural sector? There is some work showing the tight connections between the agricultural and non-agricultural sectors (for example, Haggblade et al. 2010, Gollin et al. 2021), but it remains an open question whether the most productive policies would seek to change the returns to non-agricultural investments, and in this way draw labour out of agriculture and facilitate structural transformation, or whether direct investment in increasing agricultural productivity should be the focus.

Third, can the integration of rural and urban markets in Africa provide better incentives to farmers? A lot of urban food production comes from imports meaning there may be a role for the demand side and better market integration in driving technology adoption to replace these imports with locally produced goods (for a review, see de Janvry and Sadoulet 2020). Creating market incentives that remunerate quality, especially for high value crops, may be one step towards sparking this demand side (Bernard et al. 2017). But at a more fundamental level, we must seek to analyse relevant markets and incorporate this analysis into our research on technology adoption.

Fourth, there is very little irrigated farmland across Africa. Many farmers in the region use small-scale pump and hand irrigation along streams for market gardens, especially in peri-urban areas. More than half of irrigated land in Liberia, Sierra Leone, Ghana and Nigeria is smallholder informal irrigation, not reliant on fixed infrastructure (Drechsel et al. 2006). The aggregate area covered by this smallholder irrigation remains tiny. There is a dearth of quantitative information on the availability and characteristics of groundwater across sub-Saharan Africa, but the underlying geology appears to be such that the potential for high water yield boreholes for irrigation is not widespread, so there may be important geological constraints (Xu et al. 2019). Population density may also be a major constraint to large infrastructure investments required for surface irrigation. If these constraints are binding in certain areas, is there a way to scale down large-scale infrastructure investments? An example would be the small-scale wet coffee mills that TechnoServe helped cooperatives build across East Africa (IPE 2017).

Fifth, we still know little about the role of the state in agriculture. In particular, there is not much work on crony capitalism in agriculture, or the political economy around how policy priorities or large infrastructure investments are decided specifically in agriculture.

Sixth, there is more to learn about some of the constraints we highlighted above, especially when it comes to labour, land markets and the environment. A number of multifaceted interventions have proven to be cost effective in some settings: for example, One Acre Fund in Kenya and the Niger Economic Inclusion

Programme, but much remains to be learned in identifying which constraints affect which farmers.

Finally, there are many studies about how climate change is likely to affect agricultural output in Africa and around the world. But we have relatively little understanding how farmers and entire agricultural systems might adapt to these changes.

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Appendix

List of countries in the regions of Africa:

World Development Indicators (WDI)	
South Africa	Botswana
	Eswatini
	Lesotho
	Namibia
	South Africa
West Africa	Benin
	Burkina Faso
	Cabo Verde
	Côte d'Ivoire
	Gambia
	Ghana
	Guinea
	Guinea-Bissau
	Liberia
	Mali
	Mauritania
	Niger
	Nigeria
	Senegal
	Sierra Leone
	Togo
East Africa	Burundi
	Comoros
	Djibouti
	Eritrea
	Ethiopia
	Kenya
	Madagascar
	Malawi
	Mauritius
	Mozambique
	Rwanda
	Somalia
	South Sudan
	Uganda
	United Republic of Tanzania
	Zambia
	Zimbabwe
Central Africa	Angola
	Cameroon
	Central African Republic
	Chad
	Congo
	Democratic Republic of the Congo
	Equatorial Guinea
	Gabon
	Sao Tome and Principe
North Africa	Algeria
	Egypt
	Libya
	Morocco
	Sudan
	Tunisia

FAOSTAT	
South Africa	Botswana
	Eswatini
	Lesotho
	Namibia
	South Africa
West Africa	Benin
	Burkina Faso
	Cabo Verde
	Côte d'Ivoire
	Gambia
	Ghana
	Guinea
	Guinea-Bissau
	Liberia
	Mali
	Mauritania
	Niger
	Nigeria
	Saint Helena, Ascension and Tristan da Cunha
	Senegal
	Sierra Leone
	Togo
East Africa	Burundi
	Chagos Archipelago
	Comoros
	Djibouti
	Eritrea
	Ethiopia
	Ethiopia PDR
	French Southern Territories
	Kenya
	Madagascar
	Malawi
	Mauritius
	Mayotte
	Mozambique
	Réunion
	Rwanda
	Seychelles
	Somalia
	South Sudan
	Uganda
	United Republic of Tanzania
	Zambia
	Zimbabwe
Central Africa	Angola
	Cameroon
	Central African Republic
	Chad
	Congo
	Democratic Republic of the Congo
	Equatorial Guinea
	Gabon
	Sao Tome and Principe
North Africa	Algeria
	Egypt
	Libya
	Morocco
	Sudan
	Tunisia
	Western Sahara