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Economic development typically involves a structural transformation in which a dominantly agrarian economy moves towards being more manufacturing- and services-based. However, economies of countries across Africa have an especially high reliance on agriculture, both for output and jobs, compared with the rest of the world. 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 percent of GDP in Africa, compared with a world average of about 5 percent. Moreover, the share of agriculture in GDP of 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 a lot. Panel B shows how agricultural shares of employment have declined across regions of the world in the last 30 years. Africa now has the highest share of employment in agriculture at about 50 percent, given the declines in the South Asia region, while the world average of employment in agriculture is closer to 30 percent.

There is also wide variation in these shares across regions within Africa, the highest being East and West Africa and the lowest South 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

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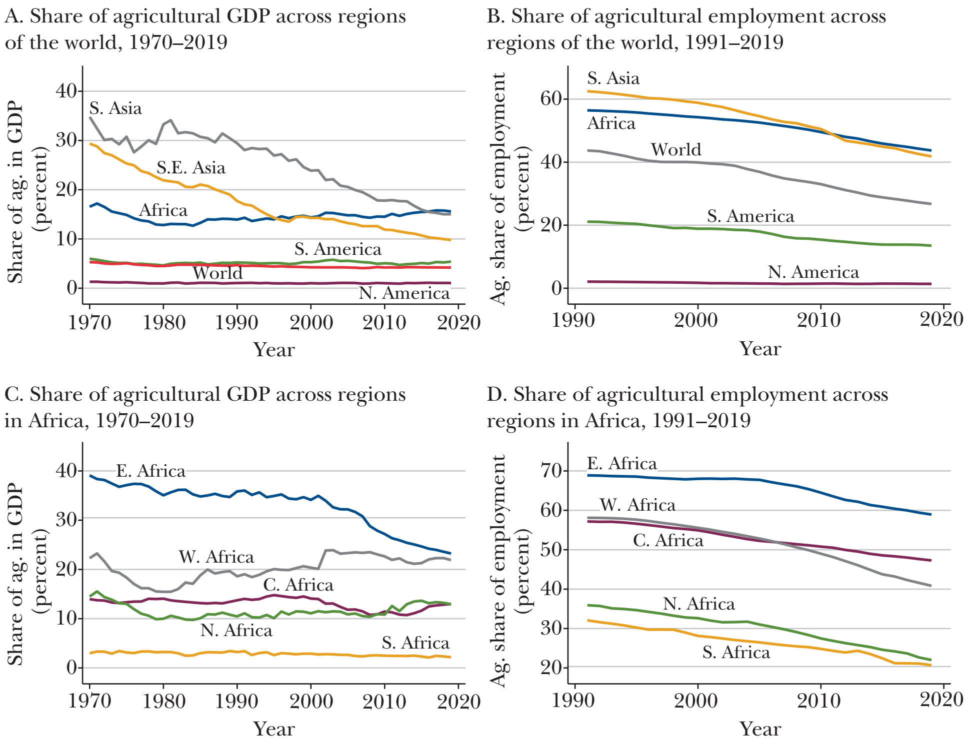
Figure 1
Agriculture's Contribution to GDP and Jobs



Source: Panels A and C are based on data from the United Nations, Food and Agriculture Organization (FAOSTAT) at https://www.fao.org/faostat/en/#home. Panels B and D are based on data from the World Development Indicators from the World Bank at https://databank.worldbank.org/source/world-development-indicators. The countries that are included in Africa and regions of Africa are described for each of these two main data sources in the online Appendix, available with this article at the *JEP* website.

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 primarily for sale. At present, about 80 percent of African farmers are smallholders with under two hectares of land, who together account for 40 percent of cultivated area (Lowder et al. 2016), although farm sizes do seem to have been on the rise recently 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, 2020; Dercon and Gollin 2014; Gollin et al. 2021). Examples of specific technological changes that improve labor productivity in agriculture that might be part of this structural transformation would include mechanization of farm activities including land preparation and transportation, and the use of labor-saving agrochemicals like pesticide. 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).

There are many historical examples of the flexibility and openness to innovation of farmers across Africa: 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 with the introduction of cocoa (Hill 1963); and more recent examples like the emergence of commercial flowers for export from Kenya and Ethiopia. But overall, these changes have not been sufficient to generate sustained productivity growth across the board in agriculture in Africa, and productivity growth in African agriculture has been slow relative to that in the rest 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 larger in Africa than it is elsewhere (Gollin et al. 2014).

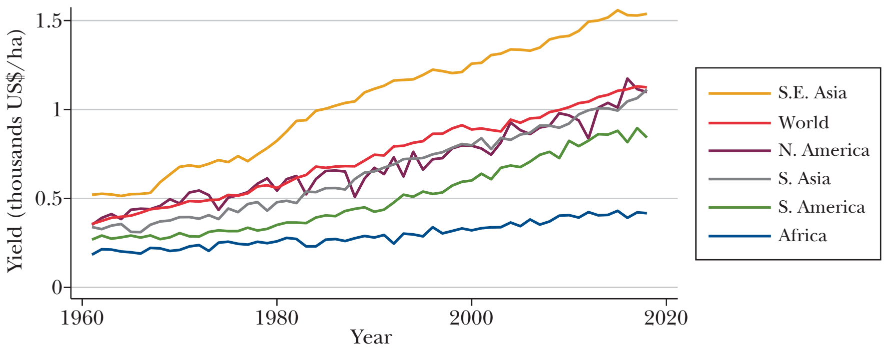
In this paper, we start with some background about agricultural productivity and technology adoption in Africa, highlighting how it has lagged. We then discuss what may explain these lags and what we know about each of these explanations. We discuss the importance of heterogeneity, along a variety of 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, so there is no large set of profitable technologies waiting on the shelf to be adopted by Africa's farmers. However, 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.[1] Figure 2 shows agricultural yields for cereals (as measured in value/hectare) in Africa versus the world over the last 60 years. Both the level and growth rate of yields in Africa lag 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 South Africa region have climbed substantially to $900/hectare in the last decade or so, while yields in countries of West Africa and

[1] 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 program (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 by Region of the World, 1961–2018
(in thousands of US dollars per hectare)



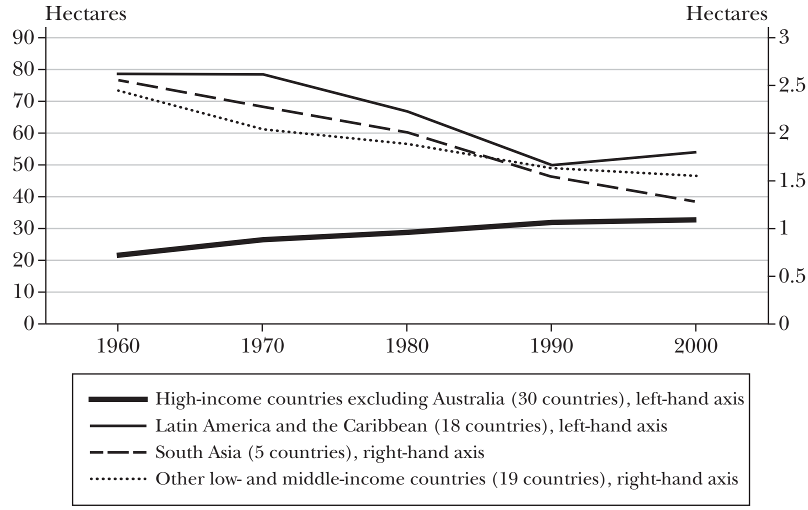
Source: United Nations, Food and Agriculture Organization (FAOSTAT) at https://www.fao.org/faostat/en/#home.
Note: Includes barley, buckwheat, canary seed, cereals not identified separately (canagua/coaihua, quihuicha/Inca wheat, adlay/Job's tears, wild rice, other minor unclassified locally relevant cereals), fonio, maize, millet, oats, rice (paddy), rye, sorghum, triticale, and wheat.

North Africa rose more modestly to about $500/hectare, and yields in Central and East Africa have risen only slightly to about $300/hectare.

Underlying these yield trends are, of course, changes in farm size, though there is much less variation across low- and middle-income countries on the average farm size. Figure 3 below 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 of these regions have dramatically smaller farm sizes than in Latin America and the high-income countries). It is worth noting, however, that data on farm size is less consistently collected and so may be noisier (Lowder et al. 2016).

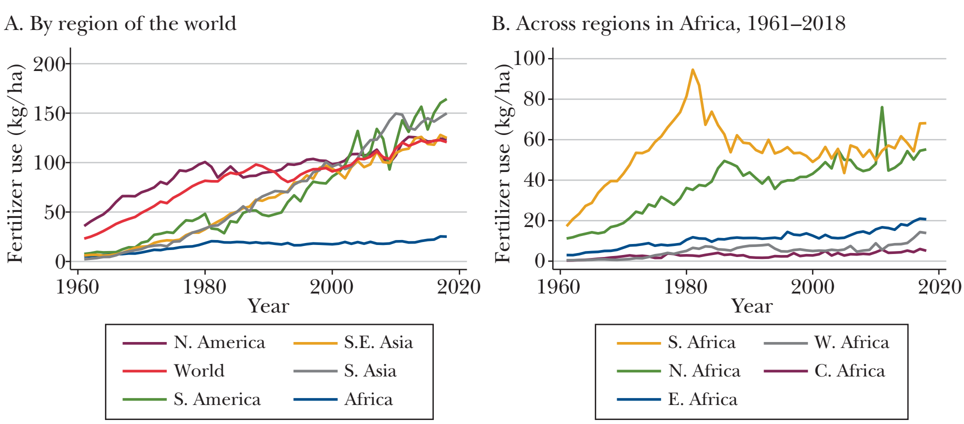
These yield gaps across the world and across Africa are largely a consequence of the dramatically different technologies being used. Technologies in agriculture involve the biological processes of plant and animal growth, coupled with the physical actions that create the uniform conditions that distinguish a farm from natural growth. Agricultural technology is embedded in seeds, breeding stock, irrigation and other water management methods, chemical inputs such as fertilizer and pesticides, agronomic practices such as fallowing patterns and plant spacing, and equipment like hand tools, tractors, or pumps. Large variation across regions is apparent along many of these dimensions. In Figure 4, we show fertilizer use comparing Africa to regions of the world as a whole, and comparing across regions within Africa. Most other regions in the world mostly caught up to North American levels of fertilization at least two decades ago. Although there have been substantial increases in fertilizer use in South and North Africa, gains in other areas of Africa appear quite modest.

Figure 3
Average Farm Size by Region of the World, 1960–2000



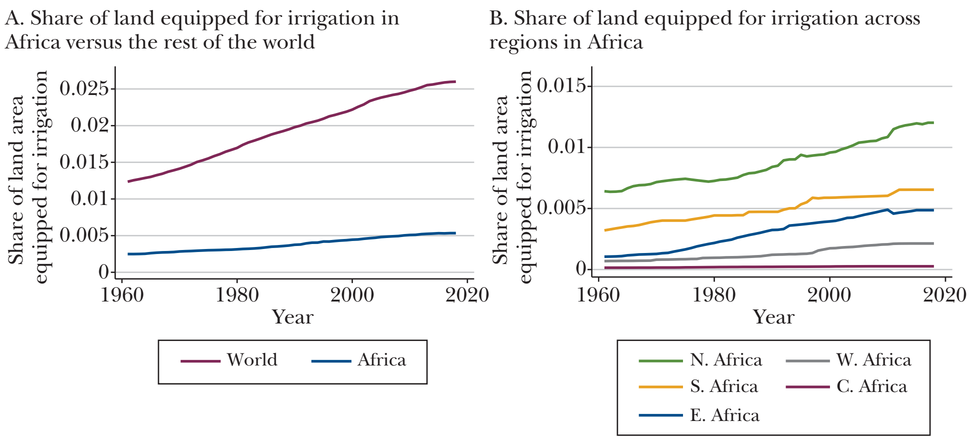
Source: Lowder et al. (2016)

Figure 4
Fertilizer Use, 1961–2018
(kilograms/hectare)



Source: United Nations, Food and Agriculture Organization (FAOSTAT) at https://www.fao.org/faostat/en/#home.

Figure 5
Trends in Irrigation, 1960–2020



Source: United Nations, Food and Agriculture Organization (FAOSTAT) at https://www.fao.org/faostat/en/#home.

In the case of irrigation as well, Africa lags quite far behind, with little sign of catch up. 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 0.025 for the world. Again, there is substantial heterogeneity across regions of Africa, with irrigation concentrated in North Africa and in South Africa (Panel B, Figure 5). Almost all farmers in West, Central, and Eastern Africa rely exclusively on rainfall for their crops.

Fertilizer and irrigation are two key agricultural technologies. As we will discuss later in the paper, these inputs also have the property of reducing heterogeneity in characteristics of land: for example, irrigation projects, to some extent, level out natural differences in supply of water to farmland. In turn, the extent of heterogeneity has implications for how widely other technologies like seed varieties and cultivation practices can be broadly shared.

The Why: Reasons for Africa's Technological Stagnation in Agriculture

Our aim here is to provide a framework for understanding the range of constraints that account for the stagnation of technological progress in agriculture 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 randomized controlled trials across 10

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), and Suri and Udry (2021)—the last review specifically for the case of Africa. Ultimately, none of these constraints taken alone seems able to explain the low technology adoption (and hence low yields) 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 interventions may end up being the most useful approach to adoption of new technologies and improving agricultural productivity. Currently, we do not know much about effective packages of interventions (we return to this in more detail below). Examples of packages include a program in Kenya, organized by a nonprofit called Drumnet, that combined training, agricultural credit, improved access to saving, input supply, and marketing assistance and showed that this led to increased adoption of a novel export crop (and the related inputs) (Ashraf et al. 2009). Also in Kenya, the One Acre Fund's program of group lending, crop insurance, regular training, input supply, and market facilitation support generated adoption of improved practices, increased use of fertilizer, and increased yield and farm profits (Deutschmann et al. 2019). A multi-faceted "economic inclusion" program in Niger with training, large cash grants, and a set of psycho-social interventions generated substantial increases in improved livestock and use of fertilizer and phytosanitary inputs (Bossuroy et al. 2021).

However, such multifaceted programs have not always been successful. The Drumnet export-promotion program in Kenya, for example, collapsed after a year when farmers were unable to meet EU production requirements. Some earlier programs of this type were costly failures, like the Integrated Rural Development Programs implemented in the 1970s and 1980s (Chambers 2013), or the minimal effects of some community-driven rural development programs (Appiah et al. 2020). We lack a clear understanding of what elements of these programs are essential and in which environments.

Farmers do show an ability to overcome these constraints when the technology is sufficiently productive (that is, if it increases yields by enough) and hence actually profitable (Suri 2011). There are many examples of technology being adopted in specific contexts, such as cocoa in Ghana and Cote d'Ivoire, flowers in Kenya and Ethiopia, and improved cassava in Nigeria. But this notion of "sufficiently productive and profitable" is limited in geographic, economic, and social extent by the heterogeneity that we discuss in the next section.

Below, we summarize some of the main constraints that have been studied in the literature and some overall findings on these constraints. We do not detail findings in specific papers—instead, we draw on the extensive review in Suri and Udry (2021) and refer readers there for a more detailed, paper-by-paper literature review.

Credit, Liquidity, and Savings Constraints

If farmers face binding credit constraints, or barriers to saving, they may not invest in new agricultural technologies. Much of the work on this topic has focused on adoption of fertilizer and/or improved seeds (which are often complementary inputs). Many countries in sub-Saharan Africa have hosted experiments with input subsidy schemes; good reviews of experiences with fertilizer subsidies can be found in Druilhe and Barreiro-Hurlé (2012) and Smale and Thériault (2018). These papers do find increases in adoption when inputs are subsidized, though the increases are small relative to the gap documented above.

Another approach is to use credit or savings to improve the quality of output, using a range of policy tools such as the provision of improved storage technologies and encouraging the use of technologies to combat carcinogenic aflatoxins that can grow on a fungus in maize. Finally, one could provide credit or savings products directly to farmers, including commitment savings technologies, which have been shown, in some cases, to improve technology use or labor (again, for detailed descriptions of the related underlying literature, see Suri and Udry 2021).

Overall, constraints on borrowing and saving seem to affect production decisions by many farmers in Africa, but only modestly. Alleviating potential credit constraints increases the use of agricultural technologies like improved seed and fertilizer, but ultimately by modest amounts and only in some contexts.

Insurance Constraints

Farmers who are not able to insure risk may bias their decisions towards low-risk, low-return technologies. This bias may be exacerbated if they are poor, in which case downside risk may be health- and life-threatening.

Financial innovation may mitigate the consequences of risk. For example, rainfall-based crop insurance might address weather risk. However, the studies in J-PAL (2016) across a number of countries find that take-up of rainfall insurance at actuarially fair rates is very low (for example, Carter et al. 2017), though high when subsidies are substantial. When the price risk of crops is insured directly, there are also impacts on the adoption of agricultural technologies.

There is evidence that when risks are insured, adoption of technologies like fertilizer and new seed varieties can improve, although important challenges remain in designing these insurance mechanisms. Improved information to serve as the basis for such insurance contracts may become available 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). Such data could help: it would get better (and independently verified) estimates of the impacts of any rainfall event (using data from rainfall stations still leaves a lot of uninsured risk for farmers as the number of rainfall stations is low and therefore does not offer complete coverage) and hence provide a much cheaper alternative to verifying the impacts of any rainfall event via in-person visits.

Finally, if farmers truly worry about downside risk given they are close to the consumption floor, guaranteeing them an income floor may also change their investments in technology and their productivity in fundamental ways. For example, Banerjee et al. (2021) find that a universal basic income in Kenya raises agricultural investments, both in terms of agricultural assets (including livestock) as well as the use of agricultural technologies.

Information Constraints

Farmers in Africa may not know about new technologies or how to use them effectively. Providing information to farmers directly, as well as through social networks, may address this problem. There are a wide variety of studies of various extension programs, public and private, but most of these studies do not find transformational effects on technology adoption (for overviews, see Caldwell et al. 2019; Bridle et al. 2019; Suri and Udry 2021). These modest impacts are found irrespective of the mode of delivering the information (for example, using direct training programs as in traditional extension or via text messaging or video messaging). While a number of studies show that farmers learn about new technologies through social networks, this new knowledge is unable to close much of the adoption gap.

Overall, extension and information programs seem to have limited effects on technology adoption, except perhaps in settings where the technologies or the crops are truly new.

High Transaction Costs and Infrastructure

Farmers across Africa face high transaction costs across multiple dimensions: both input and output markets are hard to access, with poor supply chain investments and infrastructure for many agricultural products. Search costs are high and there may often be many layers of intermediaries between sellers of the agricultural good and the final buyer (Startz 2020; Grant and Startz 2021). The traders who play an important intermediary role in farmers' access to output markets may have market power (Bergquist and Dinerstein 2020; Casaburi et al. 2013; Newman et al. 2018). Markets are often not well-integrated, though this is slowly changing in Africa with growth in cell phone adoption and use. Sometimes, farmers cannot easily sell their output or easily access inputs. The profits from new technology use may be low given this current state of infrastructure.

The literature on market access is growing, including studies that highlight the importance of inadequate supply chains for input and output markets as barriers to adopting new technology. African agriculture often seems to lack markets for quality—that is, the lack of different prices for varying quality of crops. Providing quality incentives seems to be important in driving farmers' investments in quality, but we still have a lot to learn here. There is ample evidence that farmers lose significant quantities of harvested crops to post-harvest and storage losses. At the farmer level, these can amount to between 4 percent and 8 percent of output (Sheahan and Barrett 2017). There is a small (but growing) literature on the role of technologies that avoid such losses, showing that these may improve technology use and productivity. However, again, there is room to reinforce some of these early studies.

Digital financial tools may also hold some promise to improve the agricultural value chain. Studies on these aspects have only just started, so there is still a lot to learn. An example is using technology to build better trading markets, such as the Ethiopian Commodity Exchange, a digital crop market in Uganda called Kudu (Newman et al. 2018), and M-Shamba in Kenya. A similar example in the area of crop insurance is the Kilimo Salama rainfall insurance program in Kenya, which relies on mobile money for payments (Greatrex et al. 2015).

Imperfect Labor Markets

Given the low population density in many African economies, farmers in rural labor markets may find it hard to hire the right types of labor at the right times. There is not much research about the constraints that poorly functioning labor markets play in agricultural productivity in Africa, in part because it is hard to design interventions in labor markets that seem likely to improve labor allocation and also to be implementable from a policy perspective. However, some studies have shown that large-scale investments (such as irrigation and mechanization) are not fully exploited due to poorly functioning labor markets and the inability to hire enough labor when needed.

Imperfect Land Markets

Imperfect land markets and poorly defined property rights for farmers may explain some of the low level of investments in agricultural technologies, as farmers may not feel confident in their access to the future returns on these investments. A small literature addresses how improvements in property rights may affect the use of agricultural technology. Across the literature in this area, it does seem that improvements in property rights generally increase investment, but there are exceptions.

Large-scale commercial agriculture is rare in sub-Saharan Africa, at least in part due to the barriers in gaining access to land (Collier and Dercon 2014). Land market imperfections inhibit the growth of particularly productive farms (Restuccia and Santaeulalia-Llopis 2017), preclude farmers from capturing potential returns to scale associated with mechanization (Foster and Rosenzweig 2017), and slow the development of robust value chains that can support technological innovation (Barrett et al. forthcoming).[2] However, the same customary land tenure systems that inhibit the commercialization of land 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 issues.

[2] Gollin and Udry (2021) argue that Restuccia and Santaeulalia-Llopis (2017) overestimate the potential gains to reallocating land to more productive farmers, but do not dispute the existence of misallocation due to land market imperfections.

The Where and When: The Broader Role of Heterogeneity

Many agricultural technologies exhibit an extreme sensitivity to local circumstances: nutrients, moisture, temperatures, 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 2021). 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. Such heterogeneity is almost the very nature of agriculture. Even in agricultural regions outside Africa with well-developed agricultural technology, 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/).

We believe that this heterogeneity is a 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 fertilizer. 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 percent larger than the 5th percentile yield. For comparison, the 95–5 ratio for Uganda is 9,304 percent and for Tanzania 2,558 percent (Gollin and Udry 2021). A substantial share of this variation is due to heterogeneity in soil, moisture, temperature, and other dimensions of growing conditions over space. This exceptional degree of heterogeneity is at least in part a consequence of the eighteenth- to twentieth-century history of low population density on most of the continent (itself caused in part by the slave trades and associated violence and political disruptions, as discussed in Manning 2014). The low population density makes infrastructure costs high, so that farmers rely on rainfall for irrigation and on periodic fallowing (rather than fertilizer) to maintain soil fertility (Boserup 1965). Agricultural production therefore is more tightly connected to local conditions: rainfall realizations, plot-level availability of soil nutrients, 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.

Heterogeneity in Soil and Land Quality

The nutrient composition, physical properties, and biochemistry of the soil affects the profitability of any given seed, fertilizer or other chemical input, or other agronomic practice. Sanchez (2019) provides an extensive 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 fertilizer is strongly dependent on sandiness and soil carbon content (Burke et al. 2020). These land characteristics vary in important ways across communities, at scales as small as hundreds of meters: Hengl et al. (2021) show some maps of data collected by the International Soil Reference and Information Centre (ISRIC), displaying differences in the soil acidity at a resolution of 30 meters. There is even 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 (like seed dispersal 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. (2020) show that in Morogoro Rural, Tanzania, within-village variation accounts for almost one-third of overall variation across the district in several key soil nutrients, and thus recommended amounts and types of fertilizer would vary similarly within villages. Farmers who were provided with plot-specific recommendations for appropriate fertilizer use (along with vouchers for reduced cost access to inputs) were more likely to apply the recommended fertilizer, and increased yields by over 150 percent relative to the control group.

Heterogeneity in Weather

The return 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. (2020) use an experimental crop trial meta-database to show that the profitability of adopting fertilizer 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 in crop varieties that are more resistant to poor weather realizations, and in particular to varieties that may but outperform the alternatives during poor weather realizations. 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. 2019).

Heterogeneity in Access to Markets

Scarce and low-quality road infrastructure, together with imperfect competition in transportation, generate large variation across space in both input and output prices. Atkin and Donaldson (2015) demonstrate that in Nigeria and Ethiopia, the effect of distance on prices of traded goods is four or five times the effect in the United States. Direct trucking costs in Africa are similarly 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 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). 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 it leads to spatial variation in access to these inputs and in the returns to and adoption of these inputs (as Suri 2011 shows for Kenya).

These high, heterogenous, and variable trade costs interact with the adoption of new technologies in specific ways: for example, subsidies for fertilizer only raise farmer incomes when trade costs are low (Porteous 2020).

Pervasive Heterogeneity and Technology Adoption

This pervasive heterogeneity presents challenges, both for African farmers attempting to make optimal technology decisions and for researchers seeking to understand farmer technology 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.

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. 2017).

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 and Mobarak 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. This reduces the incentive for private research. 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 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. 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.[3] For comparison, R&D spending per farmer in Brazil was about $1200 in 2000 and has more than doubled since then.

If one looks across regions of Africa, one can see substantial increases in South Africa and East Africa, where research and development 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 an annual rates of 6 percent or more from 2000 to2014, according to data from CGIAR ASTI. Conversely, countries like Togo, Gabon, and Guinea averaged annual declines of 4 percent 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's the result of low levels of agricultural research and development investment in the past.[4] 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).

Private research and development is not filling the gap. Although private R&D in agriculture has grown tremendously over the last 20-odd years and it is expected to play a stronger role in the future (Fuglie 2016), it is still only one-quarter of overall agricultural R&D. Moreover, almost all private agricultural R&D is in (and for) the developed world, as illustrated in Figure 6 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 there was a sustained research and development effort leading to multiple generations of new varieties gradually

[3] 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.

[4] 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 percent 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 percent of government spending goes to agriculture as defined here.

Figure 6
Public and Private Agricultural Research and Development Spending by Region, 2011 *(millions of US dollars, converted at purchasing power parity exchange rates)*

						EMEA		APAC	
	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	

Source: Heisey and Fuglie (2018).
Note: EMEA refers to Europe, Middle East, and Africa; APAC refers to the Asia Pacific region.

increased yields, improved agronomic performance and nutritional content, and increased resistance to pests. In India, it is common to have 20–40 new varieties of rice released each year since 1970, along with 10–20 new varieties of both maize and wheat each year, 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.

Broad or Customizable 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 customizable or that can be profitable across a wider range of circumstances.

In developed countries, there is much more customization 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 that within single farm plots in the American state of Minnesota, optimal fertilizer doses vary can by a factor of two. Recently, this customization 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 2021).

Agricultural research efforts in most of Africa have been less successful in adapting technology to local variation. In most of Africa, only extremely limited customization 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. 2018). Fertilizer recommendations to African farmers are often uniform over large areas of highly variable soils (Michelson et al. 2021).

Developing, testing, and adopting new technologies in this environment poses significant challenges. Customization requires much better feedback from a much larger and more diverse set of farmers. One promising direction is a greatly expanded use of farmer participatory trials to map heterogeneity and optimize 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). However, we first need to build up the base of relevant local information on 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); according to data on farmers from USDA (2020), this is 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. In Ghana there are only 14 agricultural research stations (0.28 per 100,000 farmers); in Malawi also only 154 (0.34 per 100,000 farmers); in Mali, seven (1.02 per 100,000 farmers); in Madagascar, 24 (0.42 per 100,000 farmers); in Kenya, 25 (0.22 per 100,000 farmers), in Cameroon, 30 (0.79 per 100,000 farmers); and in Senegal, also 30 (0.94 per 100,000 farmers). In Africa, the tests by research stations of new varieties simply 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 shows that there are discrepancies between self-reports of what farmers say they are using and the DNA results (Poets et al. 2020), though much more research remains to be done here. Similarly, the labs doing quality testing in these countries may need more investment.

As one example, there are disputes over the quality of inputs in different countries; Bold et al. (2017) and Ashour et al. (2019) argue that there is significant adulteration of fertilizer and herbicides, respectively, in Uganda, but Sanabria et al. (2013) and Michelson et al. (2021) provide evidence that fertilizer is of good quality across multiple countries. 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 research and development and agriculture extension activities. 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).

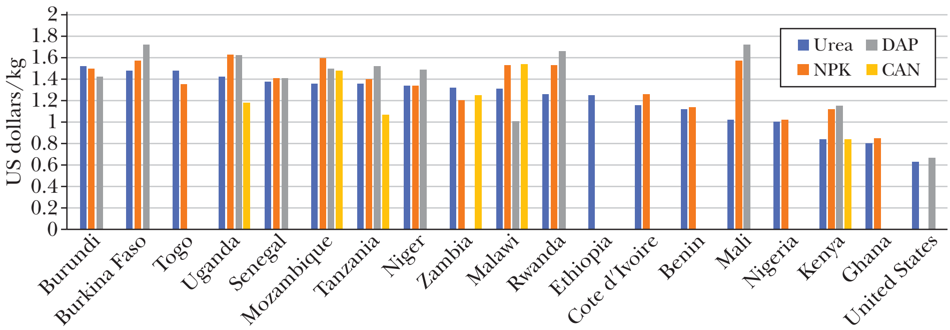
Cheaper Inputs

Many African farmers face extremely high fertilizer prices. Over 60 percent of the fertilizer in Africa was imported in 2016 (Africa Fertilizer Market Development Report 2018) and this, along with extremely high transport costs and low population density on the continent, implies many farmers often face extremely high fertilizer prices, which makes fertilizer unprofitable for them as a technology. For example, fertilizer prices in some African countries (Cedrez et al. 2020) are well over double those in the United States, as shown in Figure 7. Policy can try to target these costs directly in a multitude of ways. First, investing in infrastructure that will lower transport costs not only lowers the prices of inputs but also potentially improves market access for outputs, as lower costs of search and trading lead to improved market integration (Casaburi et al. 2013; Newman et al. 2018). Another alternative would be to encourage more local production of fertilizer or more geographically local trade in fertilizer. As of January 2021, there were only 135 fertilizer 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 price of fertilizer 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.

Policy can additionally try to target these costs directly in a multitude of ways. One obvious approach would be to subsidize fertilizer, 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. Long-term subsidies on nitrogen-based fertilizers 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.

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

Figure 7
Fertilizer Prices across Countries in Africa and the United States (2016)
(in US dollars/kilogram)



Source: Cedrez et al. (2020) for Africa; USDA Economic Research Service (2019) for the United States.

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.

Conclusion: Pressing Questions

When it comes to improving agricultural technology and productivity in Africa, we have learned much about what doesn't work, which is valuable. However, it also makes apparent how much we do not know. Here are some pressing questions.

First, we do not know enough about how to provide incentives to either the public or the private sector for the development of new agricultural technologies that are locally customized or how to provide incentives for experimentation with these technologies. Rao et al. (2019) estimate the returns to agricultural research and development and show that they remain as high as ever.

Second, are improvements in agricultural technology and productivity the most useful way for raising the standard of living and creating a path out of poverty, or should the focus be on investments in the non-agricultural sector? There is some work showing tight connections between these two sectors (for example, Haggblade et al. 2010; Gollin et al. 2021). However, it is still an open question as to whether the most productive policies would seek to change the returns to non-agricultural investments, and in this way to draw labor 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, so 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).

Fourth, there is very little irrigated farmland across Africa. Many farmers use small-scale pump and hand irrigation along streams for market gardens, especially in peri-urban areas of Africa. 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). But 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 it appears 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 of what we have in mind 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 labor, 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 Program, 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 of how farmers and entire agricultural systems might adapt to these changes.

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