Toward a Just Transition

In An Age of AgTech

The Labor Implications of Agrifood Mechanization and Digitization for Farmers in Developing Asia and Sub-Saharan Africa and the Role of Business

Annexes

Annex 1: Possible Directions of Public Policy and Business Sector Action

Public Sector: Possible Roles and Policies

Cross-Cutting

- Recognize that mechanization and digitization can significantly enhance smallholder incomes when tailored to address specific constraints.

- Develop public-private partnerships to facilitate the development of adapted technologies and business models, overcoming market failures that may exist: fund and share research on smallholders' needs to inform technology design, provide or support equipment sharing/leasing services.

- Take measures to ensure that mechanization and digitization improve occupational health and safety: adopt or convene industry around the development of safety standards, training and licensing requirements for machine operators, and develop programs targeting women and youth to receive training and ensure that it does not become an additional barrier to technology access/adoption.

- Support women's and marginalized farmers' access to technology by developing tailored financial, training, and awareness programs, and supporting research on adapted technology needs/design.

- Encourage public oversight, farmer co-ownership, or co-management of technology to ensure transparency and competition.

- Focus on the enabling environment for technology adoption by investing in public infrastructure and human resources, and adopting policies that put markets to work for people and protect them when markets fail.

- Support public research that helps inform the technology needs of female farmers in specific contexts, and proactively share that research with those designing farm equipment and digital technology.

- Ensure women have property rights and promote gender equality in technology access, addressing cultural perceptions that hinder access.

- Develop policies and programs supporting agricultural market efficiencies.

Mechanization

- Align mechanization support programs with market dynamics to prevent adoption getting ahead in certain contexts.

- Invest in relevant public infrastructure like roads and energy.

- Facilitate public-private research partnerships for adapting machinery to smallholders' needs.

- Facilitate the import of adapted farm machinery and spare parts, including to facilitate the development of homegrown manufacturing capacities where these make sense.

- Promote the incorporation of safety features in agricultural machinery/Implements and enforce regulations on equipment manufacturing to ensure rigorous occupational health and safety testing and standards; and/or convene and incite industry players to coordinate the development of voluntary standards and guidelines.

- Establish training and certification requirements for farmers before equipment use.

- Guard against land expropriation, farmer displacement, and encroachment into natural landscapes potentially associated with mechanization-enabled extensification, including by securing land ownership rights, and disincentivizing illegal land use.

- Support smallholders' access to credit and collective action capacity.

- Ensure smallholders have land titles and enforceable property rights, providing collateral for credit and machinery purchase, and protection against land expropriation of displacement.

Digitization

- Develop policies and programs supporting digital connectivity, literacy, and trust in rural areas. Mitigate high levels of digital mistrust through awareness and trust-building initiatives in partnership with technology providers.

- Address digital access and literacy gaps among specific farmer groups.

- Monitor and regulate digital platforms to prevent risks such as reduced competition, limited access to information, and unequal power dynamics:
    - Require data use disclosure requirements, applying the principles of prior and informed consent and transparency (user friendliness).
    - Adopt data release and use restrictions: restrict the release of certain types of data, and restrict certain uses of released data.
    - Require the development of operational recourse mechanisms for digital users.
    - Apply antitrust surveillance and measures to digital industries.
    - Monitor the development of risk-profiling in the provision of financial services, and develop regulation progressively without stifling innovation.
    - Ensure data privacy and security through regulations and oversight.
    - Educate farmers and the public about digital security.
- Leverage digital tools to facilitate women's access to services like extension and finance.
- Guard against threats to competition.

Business Sector: Possible Actions and Considerations

Cross-Cutting

- Collaborate with the public sector to develop solutions that address specific constraints faced by smallholder farmers.
- Explore opportunities for partnerships with the public sector to enhance market access and overcome market failures.
- Invest in technologies that not only improve efficiency but also occupational health and safety.
- Avoid reinforcing gender stereotypes or biases in the design and marketing of technologies.

Mechanization

- Participate in programs that demonstrate the benefits of technology adoption to early adopters.
- Implement equipment rental, sharing, or service programs to facilitate small farmers' access to them.
- Align technology offerings with the specific needs and economic context of smallholder farmers, with consideration for the different realities of certain groups of farmers (notably, women). Ensure technology design and promotion programs are rooted in smallholders' realities. Consider the long-term sustainability of the technology being adopted.

- Develop and manufacture agricultural machinery with built-in safety features. Mitigate risks associated with exposure to injury-prone tasks or hazardous chemicals.

- Support the establishment of industry standards and guidelines for occupational health and safety.

- Monitor and regulate equipment manufacturing to prevent the release of unsafe machinery into the market.

- Provide comprehensive training programs for farmers on equipment use and maintenance.

- Establish strong local repair and servicing infrastructure for adopted machinery.

- Implement and enforce restrictions on children's use of machinery. Engage in responsible marketing and sales practices to discourage children's use of machinery. Support children's school enrollment.

Digitization

- Encourage bundling of digital services to enhance farmers' access to information, knowledge, and markets.

- Collaborate with the public sector to support digital connectivity, literacy, and trust.

- Develop guidelines to mitigate possible occupational health and safety risks associated with the automation or robotic enhancement of farm work.

- Leverage digital tools to monitor and enhance worker health and safety.

- Where applicable, leverage digital technologies to improve transparency and working conditions for hired farm workers. Generally, ensure that digital technology is used to improve working conditions rather than exploit (hired) farm workers. Implement safeguards to prevent unhealthy competition and increased risk-taking potentially associated with the digital monitoring and measurement of work.

- Leverage digital tools to monitor supply chains for labor rights violations, and to prevent them in the first place. Leverage digital technologies to give farmers access to information and grievance mechanisms, and to monitor supply chains for child and forced labor and labor rights violations. Invest in efforts to increase workers' trust of digital platforms.

- Explore business models that give smallholder farmers a path to co-ownership of technology, data, and related rents, and enables them to shape the directions in which technology develops as well as to profit-share.

Annex 2: Key Risks, Red Flags, Opportunities, and Enablers

Farm Incomes

KEY OPPORTUNITIES	KEY RISKS
• Farmers become more productive and earn more as a result • Farmers save time on farm work and use their newly acquired time to diversify their income sources and engage in more lucrative nonfarm activities, earning more as a result • Farmers are able to produce higher quality and higher value products and hence participate in more lucrative agricultural markets, thus earning more • Farmers are able to fetch higher prices for their products, and purchase inputs at a lower price, enabling them to earn more: (they are more aware of fair market prices, are better equipped to choose when and where to sell their products, and can bypass market intermediaries that take a cut and sometimes offer below-market prices) • Farmers are able avoid catastrophic crop losses (by utilizing information advice about impending risks, like extreme weather, and working around it)	• Farmers pay for technologies that do not serve them and ultimately reduce their profitability: they are unable to generate much higher revenues, or they expose themselves to risks that end up leaving them worse off • Farmers get locked into using platforms that, over time, narrow their options and lead them to facing less competitive input and output prices
POSSIBLE ENABLERS	RED FLAGS
Mechanization benefits smallholders' incomes	
• Farmers face opportunities to sell and/or earn more if machines allowed them to increase their output or its quality or level/quality of processing • [Machinery helps farmers work faster, enabling them to grow additional and potentially more lucrative crops, engage in more lucrative additional activities, or be more responsive to climate risk]	• Government is subsidizing and otherwise pushing labor-saving machinery even though labor/time is not a constraint to achieving higher incomes: farm labor is abundant, the nonfarm economy presents minimal economic opportunities to farm workers, market linkages and opportunities to commercialize more output are underdeveloped

• Programs are in place to adapt machinery to smallholders' needs (e.g. public-private research partnerships) • Farmers are already organized and connected to input and output markets via farmers' organizations and contracting schemes, putting them in a position to utilize digital market tools to their fullest • Farmers have access to storage and have enough liquidity that they can delay the sale of their products to take advantage of higher prices • Policies and programs are in place to support agricultural market efficiencies and remove hidden taxes on agriculture	• Programs attempting to stimulate demand for mechanization services are not rooted in the realities of smallholders and weakly involve early adopters in demonstrating the benefits of adoption • Government is intervening in contexts where there are sizeable private service providers that are not credit-constrained (Mano et al. 2020 notes that public sector intervention may not be justified in such cases) • Technology adoption creates a strong dependence on outside technology providers and/or reduces farmers' options, creating vulnerability in case of a malfunction • Machinery being adopted cannot readily be fixed locally • Mechanization leads to farm simplification and reduced agroecological resilience • Mechanization leads to extensification and incomes increase at the expense of forests, natural grasslands, or other natural landscapes (and potentially with continued reliance on child labor if that was an issue to begin with)

Digitization benefits smallholders' incomes

• Policies and programs are in place to support digital connectivity, literacy, and trust, with a focus on farmers and rural areas • Farmers are choosing to use digital services outside the scope of a donor project; farmers are paying for service • Digital services address income constraints relating for example to information and knowledge, access to finance, inputs, and equipment, or markets • Thanks to digital services, farmers are more aware of fair market prices, are better equipped to choose when and where to sell their products, and can bypass market intermediaries that take a cut and sometimes offer below-market prices	• Competition is undermined leading to lower output prices and higher input prices, reducing farmers' net incomes • Farmers are excluded from services (for example, financial services), or face high prices, with limited recourse or alternatives • Data, knowingly or unknowingly released by digital service users, is used to influence their decisions and choices in ways that are unwanted or do not coincide with their best interests • Inequality increases as farmers lack the capacity to benefit from technology and data rents • See section on digital platform risks

- Digital services provide farmers actionable information and advice about impending risks, like extreme weather

- Digital services give farmers access to extension and advisory services that they previously did not have access to, or improves their relevance and quality

- Platforms are bundling services and enabling farmers to act on information and advice. For example, digital advisory services are linked with services facilitating that application of advice by improving access to inputs, equipment, finance, services, and markets

- Farmers are already organized and in a strong position to make use of production and marketing data/advice

Occupational Health and Safety of Farm Work

KEY OPPORTUNITIES	KEY RISKS
- Machinery makes farm work less strenuous - Technology is used to limit the risks of injury - Technology makes farm work more attractive as a profession, potentially helping to retain or attract youth in/to the sector	- Farmers' interaction with machinery exposes them to new hazards - The monitoring and collection of data on farmers is used to "exploit" them: farmers are pushed to work harder or take more risk to keep their jobs or maintain their wages
POSSIBLE ENABLERS	RED FLAGS
Occupational health and safety (mechanization)	
- Mechanization reduces drudgery of farm work and removes certain risks - Technology builds in safety features	- Equipment leads farmers to expose themselves to injury prone tasks, or potentially hazardous chemicals - Training on equipment use is low; training/certification is not required before equipment use

• Technology requires farmers to develop specialized skills, or makes their work more interesting	• Children use machinery
	• Access to equipment maintenance services is low
	• Equipment manufacturing is not subject to rigorous occupational health and safety testing and standards
	• Equipment does not incorporate safety features
Occupational health and safety (digitization)	
• Farmers' remuneration is based on the digital monitoring of work, making the measurement and remuneration of workers more objective, fair, and transparent	• Digital technology is used to robotically enhance farm work, including through wearable technology
• Digital tools are leveraged to ensure worker health and safety	• Farmers' remuneration is based on digital monitoring of work, leading them to compete and work harder, and take more risk to keep their jobs or maintain their wages

Hired Farm Workers' Incomes and Working Conditions

KEY OPPORTUNITIES	KEY RISKS
• The remuneration and stability of hired farm work increases (as technology increases the skill requirements of farm work)	• Farm workers see their earnings decline due to underemployment and/or a decline in their wages: (some farm workers are displaced by machines and are unable to find good jobs in the nonfarm economy; meanwhile, farm work becomes deskilled and wages decline)
• Organizations and companies monitoring forced labor and exploitative labor situations in the supply chains are able to make more efficient and targeted use of scarce monitoring and investigation resources (by using digital technology to detect potentially problematic situations and engage in a more risk-based approach)	• Farmers find themselves working more and perhaps taking on more risk in exchange for stagnant or declining wages (or to keep their jobs), (as technology is leveraged by employers to monitor workers, induce them to compete more, and ultimately extract more from them)
• Farm workers are better equipped to avoid and report forced labor and exploitative work situations: they are informed about their rights, they have records of what they agreed to, they have access to data about their work and output, they have access to grievance mechanisms	
• Child labor decreases as a result of increased productivity	

POSSIBLE ENABLERS	RED FLAGS
Employment and wages of hired (landless) farm workers (mechanization)	
• Mechanization increases the demand for farm labor (tradeoffs: it also leads to expansion of farming into natural landscapes, it increases or maintains reliance on child labor) • The nonfarm economy is absorbing (unskilled farm workers, including in jobs created by mechanization/technology such as machine maintenance and repair, and agro-processing • Labor markets are fluid: workers can readily relocate to jobs where they can better use their skills • Mechanization increases the skill requirements of farm work, (leading to higher wages and employment stability)	• Subsidies or machine sharing and rental arrangements have been put in place in a context of low demand for mechanization services among smallholders; supportive programs are not responding to a market failure
Child labor (mechanization)	
• Mechanization reduces the need for (unskilled) labor • School attendance is high	• Mechanization leads to the spatial expansion or intensification of farming operations (for example, multi-cropping), or more generally, does not result in the need for less (unskilled) labor • Children's school attendance rates are low: the cost of having them work on the farm is lower
Exploitation and forced labor (digital tools)	
• Digital tools facilitate anonymous reporting of labor violations and more continuous monitoring of labor conditions • Digital tools enable the education of at-risk groups • Digital tools use AI and advanced analytics to enable a more efficient, risk-based approach to social audits and labor investigations (for example, digital tools use AI and machine learning to detect patterns suggestive of	• A grievance mechanism that is known and trusted by those it is intended to empower is not in place • Digital tools are unknown to or mistrusted by those they are intended to empower

- forced labor on social media sites, aggregate and analyze data to identify red flags in supply chains)
- Digital tools enable the formalization of migrant worker hiring, helping to keep forced labor scenarios at bay
- Regulatory mechanisms are in place to exclude products that involved forced labor from markets, and that put the onus of clearing products on suppliers
- Farmers are organized, networked, and empowered; they can seek protection from retribution when needed

- Technology is used to survey workers leading them to work and compete more and take more risks to keep their jobs
- Social audits do not have a strong track record in terms of mitigating forced labor: (improvements in social auditing may have a positive if not necessarily transformational effect)

Equity and Inclusion

KEY OPPORTUNITIES	KEY RISKS
- Small or very small farms are able to break through the (farm-)income ceiling implied by their small land holdings by diversifying into nonfarm activities: (they are able to farm larger expanses of land, or to profitably sell or lease their land and move on from farming to other more lucrative forms of employment, increasing their incomes) - Female farmers gain time to engage in more lucrative farm or nonfarm activities, or other activities that benefit their households (for example, childcare and food preparation) - Workers are spared the most strenuous and risky farm work tasks	- Certain farmers are unable to adopt or fully make use of technologies being adopted by their peers, leading to growing inequality - Technology leads certain farmers, notably women, to have to take on more unpaid or low-paid work, and/or to lose control over household resources - Farmers are displaced from their farmland (due to the expansion and encroachment of other farms)
POSSIBLE ENABLERS	RED FLAGS
Women's welfare and gender equity (mechanization and digitization)	

• Women's incomes are constrained by a lack of time to engage in more lucrative activities; and targeted programs are in place to design and give women access to responsive machinery that frees up their time • Digital tools are leveraged to give women access to services, like extension and finance, that they could not otherwise access due to time and other access constraints • Women have property rights	• Women have less access to technology due, for example, to cultural perceptions of technology not being for women, lower access to/control over resources, or lower literacy levels • The sequencing of mechanization prioritizes activities that are typically carried out by men, freeing up men's time but not women's • Women inherit work previously done by men once it is made more "physically accessible" by mechanization • Women are less valued once their work is mechanized • Women spend more time searching for firewood due to tree clearing on farm (for machinery use purposes)
Smaller and less well-endowed farmers	
• Equipment rental, sharing, or services are in place • Smallholders have land titles and enforceable property rights, giving small and tenant farmers the bargaining power to prevent land encroachment or to seek compensation, and the collateral necessary to obtain credit and purchase machinery and other agricultural inputs. • Farmers are already well organized, improving the chances that mechanization support programs will be effective	• Technology adoption is getting ahead of market forces, notably in land-scarce and low-wage settings where there is an abundance of farm labor and little to be gained by labor-saving technology • Low digital access and literacy among certain groups of farmers • High levels of digital mistrust

Digital Platforms' Prospective Effects on Farmers' Incomes and Income Inequality

KEY OPPORTUNITIES	KEY RISKS
- Policies and programs are in place to support digital connectivity, literacy, and trust, with a focus on farmers and rural areas - Farmers are choosing to use digital services outside the scope of a donor project; farmers are paying for service - Digital services address income constraints relating for example to information and knowledge, access to finance, inputs, and equipment, or markets - Digital services give farmers access to extension and advisory services that they previously did not have access to, or improves their relevance and quality - Platforms are bundling services and enabling farmers to act on information and advice. For example, digital advisory services are linked with services facilitating that application of advice by improving access to inputs, equipment, finance, services, and markets - Farmers are already organized and in a strong position to make use of production and marketing data/advice	- Competition is undermined leading to lower output prices and higher input prices, reducing farmers' net incomes - Farmers are excluded from services (e.g. financial services), or face high prices, with limited recourse or alternatives - Data, knowingly or unknowingly released by digital service users, is used to influence their decisions and choices in ways that are unwanted or do not coincide with their best interests - Inequality increases as farmers lack the capacity to benefit from technology and data rents
POSSIBLE ENABLERS	RED FLAGS
Risk of competition being stifled and undue influence being exercised by technology providers	
- Models are being developed that are putting farmers in a position to benefit from potential rents derived from the use of their data (examples) - Data-based risk profiling: good side is that it can give farmers access to credit and other financial services in the absence of collateral or a financial history (see flip side) - Farmers are educated about their rights and the ways in which data may be used	Strong dominance of a given platform, particularly one bundling services: Platforms are bundling multiple services and increasingly creating an ecosystem of services used by a critical mass of farmers, suggesting a network effect and potential lock-in. This can be a good thing, but over time, it can create the conditions for undermining farmer choice and competitive input/output prices

• Technology providers are upholding data use disclosure standards, and committing to not using data in certain ways • Regulatory data use disclosure and restrictions are in place	• Interdependence of services offered on a platform; and cross-utilization of data by different service providers on a platform • Increase in market power of certain players supplying goods and services on the platform • Decrease in number of competitors • Release of data to technology providers • Platforms offer services for free in exchange for the release of data – could lead farmers to release data that is used to manipulate (or narrow) their choices in ways that are unhelpful and leave them worse off. • Data-based risk profiling of farmers: bad side is that farmers could be profiled erroneously and left without recourse to correct errors generated by anonymous, black box, unregulated algorithms • Shared use of data across a farm service ecosystem (risk profiling, pricing, targeted marketing, etc.) • Lack of regulations relating to the disclosure of data uses, or restricting certain uses of user data
Widening of inequality linked to use of farmer data	
• Farmers are co-owners and stakeholders in technology companies • Restrictions are placed on certain commercial uses of farmer/user data • Requirements are in place to compel the sharing/redistribution of rents derived from farmer/user data	• Free provision of service in exchange for release of data • Lack of disclosure requirements and practices relating to the release and use of data by technology companies and third parties • Lack of restrictions on the use of user data • Lack of user awareness of the risks

Annex 3: Environmental Considerations

Mechanization and digitization are not inherently green technologies and can pose multiple direct and indirect risks to the environment. Both technologies consume energy, and power tools typically rely on fossil fuels. Heavy farm equipment, especially tractors, can affect soil quality through compaction. More indirectly, mechanization can be and often is associated with potentially environmentally taxing farm intensification, which typically brings about an increase in farms' aggregate environmental footprints and a decrease in their environmental intensity (increases in output outpacing increases in environmental impact). Indirectly, mechanization also sometimes leads to the removal of a green landscape or enables incursions into natural ecosystems, impacting biodiversity, ecosystem health, and carbon storage. However, the expansion of farms facilitated by mechanization can be environmentally neutral if it involves a shift in farm ownership or the reclaiming of uncultivated lands rather than encroaching on pristine ecosystems.

While mechanization tends to be associated with or bring about larger scale farming, the relationship between farm scale and environmental friendliness is a subject of ongoing debate. It is not a given that agroecological and regenerative farming methods are incompatible with larger-scale, technology-assisted farming. In fact, with the right incentives and support, mechanization and digitization could potentially be the keys to making agroecological and regenerative farming possible at scale—even if this is not how these technologies have predominantly been applied to date.

Both mechanization and digitization also have the potential to be applied in environmentally beneficial ways, and may, in some instances, help overcome tradeoffs between environmental protection and resilience, and agricultural productivity. Some forms of mechanization and digitization allow the more precise application of inputs, offering the means to at least partly curb the environmental impacts of farm intensification. Going forward, they could also be used to infuse farming with the data- and knowledge-intensity that are the hallmarks of regenerative and agriculture. Mechanization has played an important role in the adoption of conservation agriculture, which can be associated with soil health and carbon sequestration benefits. In China, the government is looking to mechanize plastic mulch collection to restore soil health where it has been degraded by plastic pollution.

Digital technologies could potentially help increase producers' incentives to uphold higher environmental standards. By facilitating the traceability of products and inputs and reducing information asymmetries in value chains, digital technologies could help increase suppliers' accountability and incentives to hold production practices to higher (environmental) standards. Digital technologies could also potentially incentivize environmental stewardship by facilitating performance-based finance. In other sectors, data has been a catalyst of performance-based finance schemes, which instead of making upfront investments, pay against results. In the context of farming, enhanced availability of data on farm management practices and associated pollution could open new possibilities for developing performance-based finance for green farming. It is possible to imagine such data becoming available in a scenario involving the use of sensors and the partial automation of input application. This possibility points to a possible role of the public sector in piloting novel financing schemes for the sector.

The potential of both mechanization and digitization to help green agriculture also lies, importantly if less directly, in their potential to enhance farms' profitability, giving them the resources and capacity to think green. In this respect, the experience of countries like China and Vietnam are informative. In both cases, advances in mechanization and farm productivity have resulted in significant harm to the environment, but also helped overcome the deepest forms of poverty and food insecurity, arguably making it possible for these countries to presently make agro-environmental sustainability a national priority.

The potential for digitization to help green agriculture is evident, but its green orientation should not be assumed. In general, digital and big data technologies are widely expected to help

farmers, including small ones, make more informed production and marketing decisions by enhancing access to information, knowledge, technologies, and markets, including by lowering their cost. If they are deployed with a green orientation, digital technologies could help overcome all sorts of barriers to greening, including ones relating to cost, time, knowledge, information, and motivation. However, the environmental benefits of digital agriculture should not be taken for granted and may benefit from becoming an explicit objective of public support or intervention.

Annex 4: The Evidence Basis (and Status of Technology Adoption)

This annex briefly summarizes the basis on which we are able to report findings. Most of it is empirical evidence drawn from academic studies and reports on technology adoption by farmers in various LMICs. While some of the study's findings are abundantly supported or informed by available empirical evidence, others are more strongly supported by theoretical expectations. With respect to mechanization, its effects on productivity and incomes have been more studied than its effects on working conditions or its specific effects on landless and female farmers. With respect to digitization, some risks and opportunities have been thinly documented because they are still emerging or prospective. In some countries, the process of mechanization has occurred over many years, in various waves; in contrast, most digital applications are incipient or experimental. We know more about the impacts of mechanization, while we are largely speculating, yet hopeful about the impacts of many digital tool applications.

While the paper is not focused on the question of why farmers do or don't adopt particular technologies, some reference to patterns of adoption is required. In the discussion of impacts, we sometimes distinguish mechanization and digitization, but this is not always appropriate as the two represent a continuum of technological solutions that present considerable overlap in terms of their functionality. In a variety of ways, and with a variety of aims, both mechanization and digitization enhance farmers' capabilities. Both save them labor and time and help them incorporate information and knowledge in their work. Digital technologies also address information asymmetries and transaction costs in ways that machine tools typically do not.

Evidence on the Effects of Mechanization

The mechanization of smallholder agriculture has progressed and been studied extensively, such that there is rich empirical evidence on its effects on smallholder farming systems in LMICs. These effects are multidimensional, context specific, and varied, and also to a large degree, positive. While the evidence on agricultural mechanization is global, much of the evidence pertaining to smallholders comes from Asia—both Southern and Eastern Asia—where mechanization is far ahead of where it stands in Sub-Saharan Africa. This can be seen by looking at the number of tractors per 1,000 farm workers across regions (Figure 1), although this is an imperfect measure of mechanization.
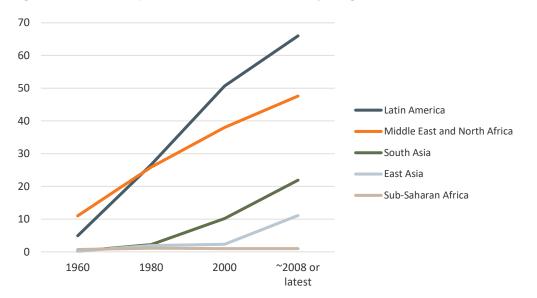
The mechanization of smallholder farms is well advanced in some Asian countries, although not all (Diao et al 2020). The region has a long tradition of animal plowing and the use of small machinery. In some countries where both small and large farms co-exist, the initial adoption of tractors and other motorized equipment took place on the larger farms, but when smaller, less expensive equipment was developed also began to be adopted on smaller farmers, especially from the 1990s onward. In countries whose agrarian structure was dominated by very small farms—for example, China and Vietnam—the impetus to mechanize came a decade later as part agricultural intensification, in the context of significant rural out-migration and rising labor costs. Use of two- and four-wheel tractors and combine harvesters is now widespread. Large irrigation systems in parts of Asia were the venues for accelerated mechanization relating to water management, land preparation, and other functions. Small, motorized water pumps were also widely adopted in South Asia. Mechanization came later in Myanmar (following its early 2010s reforms) and its spread is more modest in Indonesia and the Philippines (due to policy constraints, as well as Cambodia and Laos where rural labor is still inexpensive and relatively abundant).

The advance of mechanization in developing Asia was typically driven by rural labor market conditions and enabled by a combination of factors. The latter included the provision of government subsidies, investments in rural infrastructure (especially roads and electricity lines), measures to improve tenure security and access to finance, development of a local machinery manufacturing capability, and the emergence of a competitive system for equipment rental and/or the provision of commercial agricultural mechanization services. Nowhere in the region has farmer

ownership of large equipment been common—many forms of mechanization are tied to efficient rental or service markets (Daum and Birner 2017; Diao et al. 2020; Belton et al. 2021).

Within Asia, the evidence is particularly abundant on the productivity effects of mechanization on farms. There is also significant evidence on the employment, income, and other welfare (for example, food security) effects of mechanization. The evidence is more developed for smallholder farming households than for hired farm workers and specific subgroups of farmers including women. There is also some evidence on the environmental effects of mechanization. While these effects are beyond the scope of the paper, it is important to note that mechanization has both negative and positive effects on the environment, and that environmental considerations could and should be among the key drivers of mechanization trends going forward.

Agricultural mechanization is far less developed in much of sub-Saharan Africa and its development has been more uneven over time. While estimates of mechanization are challenging and quite varied, humans are the main power source for agricultural production in Sub-Saharan Africa[1] (Diao et al. 2016). Government-driven mechanization efforts predating the 1980s are considered to have failed (Pingali 1987 in Diao et al 2016); and by some accounts, the availability of farm power declined during the 1980s and 1990s (Mrema et al 2008 in Diao et al. 2016). Pockets of mechanization and automation have tended to occur in areas where agricultural products such as cotton are produced for export markets (Campbell 2022). For staple food production, mechanization rates at quite low nationally. Higher levels of adoption appear to occur in certain districts or regions that are comparatively land abundant and have good market access. Some important food staples in Sub-Saharan Africa, such as root crops, are not very amenable to mechanized production functions.

Figure 1: Tractors per 1,000 Farm Workers by Region, 1960–2015

Source: Fuglie et al. 2019 based on FAO 2019. Note: In Fuglie, the latest year is 2015, but FAO discontinued the number of tractor indicators in 2009 and data up to that point is not always available.

Nevertheless, interest in Sub-Saharan Africa's mechanization has reemerged in recent years, driven by renewed public sector support and instances of adoption dynamics. This is expanded upon in Box 1. In the Fogera Region in Ethiopia, for example, the use of motorized pumps has expanded rapidly in recent years, mainly as a result of a set of enabling factors that includes credit accessibility and distribution partners, hiring companies, and sharecropping (Glatzel et al. 2018). There is broader evidence of emerging private markets for machinery and services

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[1] Mechanization levels in North Africa are on par with those in Asia and Latin America (Diao et al. 2016).

within the region (Daum and Birner 2020; Diao et al. 2014; Takeshima et al. 2015 in Daum et al. 2020). Moreover, according to Daum et al. (2020), the recent experience of Asian countries indicates that "mechanization can unfold rapidly once a real demand and enabling environment exist (Biggs and Justice 2015; Diao et al. 2014; Wang et al. 2016)" (Box 2). In that respect, Tanzania is among the countries that is quickly forging ahead (Box 3).

Box 1: Support for mechanization in Sub-Saharan Africa: the new wave

In the 1960s and 1970s, several countries in Sub-Saharan Africa (SSA) initiated state-sponsored mechanization projects as part of efforts to promote agricultural modernization. However, while tractor availability increased during this period, it did not translate into the widespread adoption and use of tractors by farmers. Wide-scale demand for mechanized tillage failed to materialize and limited farm intensification was observed. In subsequent decades, attention shifted toward supporting equipment considered more suitable for smallholder farmers, including low-power mechanical equipment and equipment involving the use of draft animals. However, these efforts also failed to translate into widescale adoption and by the 1990s, both the number of tractors and interest in draft animal traction had declined significantly in SSA, in contrast to other developing regions.

Nonetheless, interest in promoting mechanization including the use of tractors has returned, seemingly encouraged by signs of growing demand and adoption for such equipment. Observers note that the use of tractors for power-intensive activities like tillage has become more common in certain areas. One possible contributing factor is that, since the late 1990s, draft animal populations have been decimated by epidemics, drought, and rangeland decline. More positively, tractors adoption has likely been enabled by the development of rental services, typically offered by large- and medium-scale farmers looking to amortize their equipment investments. Governments in SSA have taken note and increasingly become mobilized around the development of equipment hire and spare part services.

Despite these trends, questions persist about how tractors can truly benefit the majority of smallholder farmers in SSA. Recent studies in SSA have shown that tractor use has boosted farm output by increasing farm intensification and yields, or leading to farm expansion. However, the outcomes vary across different farming systems and some experts feel that more, rigorous studies across diverse agroecological conditions and farming systems in SSA are needed to guide appropriate mechanization policies.

Source: Based on Magezi et al. 2023.

The mechanization of Asia's smallholder-dominated farms is comparatively much further along. In countries like China, Malaysia, and Thailand, tractors, power tillers, and basic farm machinery are commonly used. In Thailand, a majority of rice farmers use a combination of two-wheel and four-wheel tractors for land preparation, all farmers use combine harvesters for harvesting and threshing across seasons (Mataia et al. 2016), and many use power sprayers for seeding and pesticide application (Manalili et al., 2015 in Mataia et al. 2016).[2] In countries like Vietnam,[3] India, and Bangladesh, basic machinery is prevalent, although there continues to be significant reliance on manual labor for certain tasks. However, precision agriculture technologies, automated systems, and even combine harvesters are used in pockets or more experimentally.

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[2] Moreover, they have largely adopted advanced models of combine harvesters that include storage bins for grain, eliminating the need for bagging and hauling (Matai et al. 2016).
[3] In Vietnam's rice basket region, the level of mechanization is not far behind that of Thailand. Land preparation and harvesting are fully mechanized, even though some of the machinery used is less advanced.

Box 2: Smallholder farm mechanization: the case of India

In India, where agricultural mechanization took off during the 1950s, farm power availability is estimated to have increased eightfold over the course of seven decades, from 0.25 kilowatt per hectare (kW/ha) in 1951 to 2.02 kW/ha in 2017 (Gulati and Juneja 2017). Daum et al. 2021 offers the following account of India's agricultural mechanization over that period. From the late 1950s to 2010, the number of tractors rose from 37,000 to above 5 million (Singh et al., 2014, Singh, 2015). In 1960, there was one tractor per 3,600 ha; in 2013, this figure reached one tractor per 24 ha (Bhattarai et al. 2018). Early on, land preparation is the key function that was mechanized, and it was followed by irrigation and processing. More recently, there has been an uptake of zero tillage equipment, laser land levelers, and combine harvesters (Singh 2015). Mechanization began mostly on large farms: during the 1960s, 96 percent of tractor owners possessed more than 10 ha (Singh 2015). Later, farmers owning 4–10 ha acquired smaller tractors, and later still, hire markets emerged to serve even smaller farms (Binswanger, 1986, Diao et al., 2014). In the 1970s, 60 percent of the annual use of tractors was for service hire (Singh 2015). By 2010, 38 percent of all tractors were owned by farmers with more than 10 ha, while farmers with less than two hectares owned 1% of all tractors (Bhattarai et al. 2018).

Evidence is particularly developed on the productivity effects of mechanization on farms. There is also significant evidence on the employment, income, and other welfare (for example, food security) effects of mechanization. The evidence is more developed for smallholder farming households than for hired farm workers and specific subgroups of farmers including women. There is also quite abundant evidence on the environmental effects of mechanization. While these effects are beyond the scope of the paper, it is important to note that mechanization has both negative and positive effects on the environment, and that environmental considerations could and should be among the key drivers of mechanization trends going forward. It is critical that efforts supporting further mechanization treat these environmental dimensions as a central concern and not be dissociated from considerations on household welfare.

Box 3: Tanzania: a frontrunner in tractor adoption within Sub-Saharan Africa

Since the 2000s, a rapid uptake of tractors has made Tanzania one of the most mechanized countries in SSA. Most of the uptake has been in two-wheel tractors, consistent with the government's policy aimed at promoting suitable mechanization (Agyei-Holmes 2016); but there has also been some adoption of four-wheel tractors for use in lowland rice and maize farming (Mrema et al. 2020). Tractors in use in Tanzania are primarily ones that have been imported from Europe and Asia, some of them purchased by private entrepreneurs and affluent farmers, and some imported in bulk and distributed at subsidized prices by the government. Tractor use has seemingly[4] been facilitated by private rental services that travel between areas, aligning with cultivation seasons (for rice, sunflower, cowpea), as well as by second-hand tractor markets.

Source: Based on Magezi et al. 2023.

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[4] Studies are limited

Evidence on the Effects of Digitization

Empirical evidence on the effects of digitization in smallholder farming systems in LMICs is far more limited. Given that digitization got a later start, a relative lack of evidence on its effects is to be expected; however, evidence is not only largely based on project-scale and project-supported instances of adoption, but it also points to rather widespread and persistent challenges with digital services' sustainability and scale-up.

If digital technologies continue to hold promise with respect to the transformation of smallholder farming, there is a huge gap between possibility and practice. A relatively large literature analyzes the potential of digital innovation to transform the functioning, efficiency, and equity of agricultural markets by addressing critical market and institutional failures in LMIC contexts (Abate et al. 2023). However, a 2019 study of agricultural digitization in Africa estimated that about 6 percent of the addressable market had been realized (potential estimated at EUR 2.3 billion in revenues) (Tsan et al. 2019). And while data on the adoption of digital tools and platforms by smallholders are quite thin, it is widely acknowledged that few digital technologies have been adopted at scale in Sub-Saharan Africa. The gap between aspiration and realization has been noted by multiple studies (World Bank 2016, Fabregas et al. 2019, CTA 2019, Steinke et al. 2021 in Abate et al. 2023). As noted below, the situation is a bit different in developing Asia.

There are a few cases of digital technologies that have been adopted at scale in the African context. A 2019 study on the digitization of African agriculture found that a small minority of services—some 15 companies focused on providing digital advisory services—had begun to reach notable scale with at least 1 million registered users (**Table 1**) (Tsan et al. 2019). A 2023 study on the topic also notes that there have been "significant success stories that are worth mentioning" including M-Pesa, which is not specific to agriculture although its relevance has been noted in fresh fruit value chains. Others are iCow and KAZNET, which have been relevant to livestock farmers in semi- arid and arid regions; M-Kilimo in Tanzania and Kenya, and WeFarm in Kenya and Uganda.

On closer look, however, even these "success stories" can seem inflated. Notably, a registered user on a digital platform is not necessarily an active user of that platform, or one who is willing to pay for service. The 2019 study estimated that only a fraction of registered users—on the order of 15–40 percent of them—made active use of the services in question (Tsan et al. 2019). And, even in Kenya, one of the pioneers and frontrunners of digital financial services in the region, the most widely adopted tools—notably the M-Pesa and M-Shwari digital payment platforms—are not widely used by smallholder farmers and agricultural households (Abate et al. 2023). One 2022 study estimated that only about 15 percent of Kenyan farmers used mobile financial services to make payments and 1 percent used them to obtain agricultural loans (Parlasca et al. 2022 in Abate et al. 2023).

The digitization of smallholder agriculture has progressed to a greater extent in Asia. There, the public sector has in some cases played a driving role in the provision and scaling

Table 1: Top 20 digital platforms by number of registered users, 2017

Solutions	Registered Users	Use Case
Ethiopia 80-20 hotline	4m	Advisory Services
MNO Intermediary (multi-country)	3m	Advisory Services
Agribusiness digital platform	2m	Advisory Services
Farmer connectivity platform	2m	Advisory Services
ACRE Africa	1.7m	Financial Inclusion
Bank of Kigali/TecHouse	1.5m	Financial Inclusion
WeFarm	1.4m	Advisory Services
MNO (multi-country)	1.3m	Advisory Services
ZIAMIS	1.1m	Advisory Services
Esoko Digital Farmer Service	1,	Advisory Services
Econet EcoFarmer	1m	Advisory Services
Safaricom DigiFarm	950k	Market Linkage
Arifu	900k	Advisory Services
iCow	822k	Advisory Services
Pula	611k	Supply Chain Mgt
Digital Green	500k	Advisory Services
Agroforce/Virtual City	500k	Advisory Services
Waterwatch Cooperative	500k	Market Linkage
RATIN	400k	Advisory Services
Mobigrow/KCB	380k	Market Linkage

Source: Tsan et al. 2019

up of digital information and advisory services. China, in particular, has largely mainstreamed the use of digital tools in its public extension and advisory services; and India has recently taken steps to follow suit (notably, with the government partnering with the digital video-based extension NGO, Digital Green, MoA&FW 2023). Digital tools developed by the International Rice Research Institute (IRRI) have also had significant reach across the region (Rice Crop Manager, RiceAdvice, Rice

Crop Calendar, iRiCE, SMARTSeeds app, GRiSP science portal). And in recent years, several Asian countries have seen a real take off of private e-commerce and land brokerage platforms. In China, agri-e-commerce platforms like Alibaba and Pinduoduo have attracted millions of buyers and sellers; and the online farmland brokerage platform Tulia has facilitated extensive farmland transfers.

While the supply of digital agricultural services is rapidly developing, the sector has yet to find a clear path to commercial or economic viability. While tools and pilots have proliferated, many of them initiated by donor-funded NGOs,[5] few have secured a user base or business model that would allow them to graduate from project status and make them self-sustaining. Donor and NGO driven technologies have generally demonstrated low levels of sustainability, even when their initial uptake has been high. A 2019 study of agricultural digital service companies in Sub-Saharan Africa found that, if 70 percent of surveyed enterprises were generating at least some revenue, 74 percent were not breaking even.

For this lack of commercial sustainability, there is a range of possible explanations. A central one is that many digital services are based on flawed assumptions about users' realities, including their information needs and technology use preferences and capabilities (Dodson et al. 2013, Masiero 2016, in Steinke et al. 2021). This has led to a frequent mismatch between the services on offer and users' needs and realities, including their perceptions, habits, and technology use constraints. There has been a failure to adequately address the underlying constraints to adoption; and limited success either designing responsive products or convincing farmers that products are worth paying for after they are no longer offered for free (or at a highly subsidized price).

There has also been limited success diversifying revenue streams. Although most (80 percent of) revenue-generating digital service enterprises rely on several sources of revenue, digital startups in Africa have not been able to widely rely on advertising as a source of revenue (possibly on account of their target population's low levels of purchasing power), or otherwise monetize user data (Abdulai et al. 2023, Tsan et al. 2019).

Experience shows that farmers are unlikely to pay for digital agricultural services, at least or especially advisory ones (Tsan et al. 2019). A likely implication is that digital solutions do not create enough value for end users by, for example, helping them improve their yields and output or the quality of their products, or reduce production costs and crop losses, or obtain higher prices for their products. However, it is also possible that value is created but not fully perceived, or that other social and behavioral factors inhibit users' willingness to pay. Digital advisory applications, for example, have been found to often lack feedback mechanisms, not address farmers' information needs in timely or qualitatively apt ways, be out of sync with farmers' technological capabilities and habits, struggle to gain users' trust, and weakly influence farmers' decision-making (Aker et al.2016, Fabregas et al.2019, Sulaiman et al. 2012, Wyche and Steinfield 2016, Baumuller 2018, Nakasone et al. 2014, all in Steinke et al. 2021).

In Africa, the multiplication of digital agriculture pilots potentially reflects an underestimation of the systemic barriers that continue to inhibit the earnest takeoff or success of digital agriculture. Despite real progress in mobile phone penetration, internet connectivity, smartphone access and digital literacy remain major barriers to the adoption or full use of digital technologies (Box 4). Meanwhile, the effectiveness of digital agricultural services to farmers is likely held back by the underdevelopment of a softer kind of infrastructure: a variety of agricultural information systems sometimes referred to as "middleware." These barriers cumulate, as alluded to above, with the challenges posed by the complexities of agricultural markets that involve "multiple layers of formal and informal exchanges, [and] intransigent structures and agents" (Abat et al. 2023). Ultimately, the digital tools on offer tend to inadequately address these barriers and complexities.

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[5] As of 2019, about 80 percent of investment in digital agriculture was driven by donors (including private ones), and 20 percent by the private sector (commercial) (Tsan et al. 2019).

Box 4: Systemic barriers to digital agricultural services

A central barrier to the takeoff of digital agriculture lies in the underdevelopment of pertinent physical infrastructure in rural areas. That infrastructure includes broadband supply, internet data routes, mobile telecommunications, satellite coverage, network infrastructure, and data centers.

As of 2019, the average cost of any entry-level second generation (2G) or third generation (3G) wireless device accounted for over 70 percent of the average farmer's monthly income in Sub-Saharan Africa, compared to 17 percent in India. Moreover, under 40 percent of rural areas had 3G network coverage (versus about 70 percent of urban areas). Mobile-based services relying on messaging services were more widely available, but these services generally do not offer the level of customization made possible by farmers' geolocation.

Another barrier to the takeoff of digital services in agriculture—or at least services that are strongly beneficial to farmers—lies in the underdevelopment of public agricultural data systems. This "middleware" encompasses things like farmer registries, databases of georeferenced soil and agronomic data, pest and disease surveillance systems, and weather data infrastructure. This infrastructure, these systems, and the data they avail are critical to offering farmers effective solutions.

Other potential barriers to the development of digital services in agriculture may include legal and regulatory restrictions relating to e-commerce and other digital services; and other factors that may dissuade private investment (including on the part of foreign firms) such as the weak protection of digital intellectual property rights, a lack of transparency in regulatory development and implementation, and restrictions on the participation of foreign firms.

Unlocking the promise of digital technologies may lie in the development of digital products, platforms, or ecosystems that better address these constraints and complexities. Many ideas for improvement are on the table and are already reflected in recent digital technology trends.

To develop more appropriate and response solutions, some emphasize the need for more genuinely user-centered and problem-oriented design that departs from the prevalent model of a solution looking for a problem. This can be done by using co-design methodologies that directly involve diverse future users in the development of solutions and start from an analysis of challenges rather than the possibilities of a particular digital technology (Steinke et al. 2021).

Digital approaches may be able to reach more digitally excluded farmers through stronger integration with more "conventional" services. For example, this could involve more strongly leveraging field agents and community point persons (Ghana study). Rice Crop Manager (RCM) has deployed such an approach in India, where advice is disseminated not only via an app but also via brick-and-mortar RCM centers equipped with ICT and trained extensionists. Interestingly, a study showed that farmers often bypassed the free advice offered by public RCM centers, preferring to obtain RCM advice from trusted and nearby private input dealers for a fee. Kenya-based Shamba Shape Up is another digital service that has sought to digital and physical advisory services (with mobile messages complementing interactions with extension agents).

For some, increasing the value of technologies on offer lies in the development of more "end-to-end" digital services that address multiple constraints on a single platform. This means moving beyond the development of "piecemeal informational apps" (Abate et al. 2023). In that respect, bundled services that offer not only information but also facilitate payments and transactions may hold more appeal to farmers. Widely seen as a path to building more viable digital service platforms, the bundling of digital services is already an ongoing trend. A 2019 survey of digital agriculture solutions for Africa found that over 50 percent of active digital agriculture solutions

combined more than one use case (Tsan et al. 2019). Impact studies have found that bundled services are associated with higher (self-reported) increases in farmer income, in the range of 20–100 percent (in comparison to 20–40 percent) (Tsan et al. 2019). As discussed, the bundling of services and creation of integrated platforms may also be associated with prospective risks relating, among other things, to the protection of market competition and choice.

Another consideration is that the long-term public provision or subsidization of certain digital services may be justified. Indeed, the public sector offers many services that have no or limited path to commercial viability. Less than a path to commercialization, the digitization of such services may offer a means of increasing value for public money by enabling them to reach more users and enhance the quality of their offerings.

Limitations in scale, to date, are not a reason for complacency in terms of the potential risks that could be associated with the upscaling of digital solutions. Given the enduring potential of digital technologies to transform smallholder agriculture, and considering the particular vulnerabilities of the target user population, there is a need to proactively identify and manage a range of risks that could be associated with a wider-scale adoption of digital technologies by smallholders. More than 25 percent of smallholder farmers in countries like Kenya and Senegal report access to smartphones and these and other relevant numbers are projected to grow quickly (Tsan et al. 2019).

There is a literature, mostly derived from digitization experiences in high-income countries (in and beyond agriculture), that examines the potential unintended consequences of digitization. That literature is interested in outcomes relating to market power, control over food production and food systems, implications for alternative production systems (for example, agroecological and smaller scale), and farmer equity and choice.

There is a literature that is concerned with the potential for certain digital technologies, especially platforms, to be associated with lock-in effects, and the vertical integration of agrifood supply chains (including input provision, advice, and farm management services). This literature builds on the economic literature on network economics, which describes how networks and lock-in effects can arise in tandem. Going further, a more "activist" body of literature expresses concerns about the potential for full-service digital platforms and other data-based technologies to play into the concentrated corporate control over inputs, markets, farming systems, and farmers—and detrimental uses of this market power. Such concerns are expressed by both civil society organizations, such as GRAIN and the ETC group, which tend to view the activities and offerings of large agribusiness firms with suspicion, as well as a number of academics. Concerns exist, for example, about the use of technology (such as CRISPR gene editing) to justify the privatization and control over agricultural inputs and equipment, including but not limited to seeds; or the use of platforms that integrate agricultural advice and markets (such as Climate Fieldview) to undermine input and output market competition. Such platforms can incite the purchase of branded inputs, and the sale of agricultural outputs, from/to a single seller/buyer firm, while releasing large quantities of data to be used for commercial purposes. While such concerns apply first and foremost to high-income settings, concerns are also raised in relation to services targeting smallholders in LMICs (ETC Group 2021, Hackworth et al. 2020).

An intersecting literature exists on the consequences of various configurations of farm data ownership and uses in the digital era. That literature is concerned with the manipulation of users for profit, including scenarios that involve influencing purchase decisions, or excluding users from accessing goods and services (e.g. credit, insurance). For example, fintech companies use a wide range of social and environmental data to determine smallholder farmers' creditworthiness and administer insurance services. This can be beneficial, in for example overcoming asset-poor farmers to obtain services despite a lack of financial history, collateral, or guarantees. However, it can also result in their exclusion from service, in an unregulated space. The literature is also concerned with the contributions of data ownership to lock-ins and a loss of competition (a lack of data transferability or platform interoperability can result in locking in farmers, or simply excluding them). These and other concerns are not unique to LMICs, agriculture, or smallholders, but

vulnerabilities may be particularly pronounced in contexts where consumer literacy, digital sophistication, and protections are evidently weak.

Annex 5: Technology Typologies

Types of Mechanization Technologies

This paper distinguishes four broad groups of mechanization technologies: (1) land preparation, (2) seasonal field work and irrigation, (3) animal management, and (4) primary processing.

- *Land Preparation*

Land clearing, land levelling

- *Seasonal field work and Irrigation*

Ploughing, seeding/sowing, fertilizer and pesticide spraying/application, transplanting, harvesting/picking, water pumping and irrigating

- *Animal management*

Milking, feeding, watering, fishing

- *Primary Processing*

Threshing, winnowing, shelling, cleaning, milling, cutting, pressing, grinding, chipping, drying, cooling, pickling/salting/fermenting, packaging.

Box 5 offers some examples of low-power and hand-held power equipment, which are often well-suited to smaller farms.

Box 5: Examples of low-power or hand-held power equipment

- Power Tiller: Similar to a two-wheel tractor, a power tiller is a small, multi-purpose machine used for soil cultivation, weeding, and other tasks. It is often equipped with various attachments for different agricultural operations.

- Handheld Cultivator: This is a manual tool powered by human effort. It is commonly used for small-scale cultivation, weeding, and aerating the soil. Handheld cultivators are simple, lightweight, and suitable for garden or small plot use.

- Mini-Combine Harvester: A mini-combine harvester is a compact harvesting machine designed for small farms. It combines harvesting and threshing functions and is suitable for crops like rice, wheat, and other grains.

- Seed Drill: A seed drill is a precision planting device used for sowing seeds at a controlled depth and spacing. It ensures efficient use of seeds and can be operated manually or attached to low-power tractors.

- Manual Sprayer: While not a mechanical tool, manual sprayers are commonly used for applying pesticides, herbicides, or fertilizers on crops. They come in various designs, including backpack sprayers and handheld pump sprayers.

- Row Planter: A row planter is a simple device for planting seeds in rows. It can be manually pushed or pulled, and it helps in achieving proper seed spacing and depth.

- Chaff Cutter: A chaff cutter is a mechanical device used to cut straw or hay into small pieces for livestock feed. It is often operated manually or with a small motor.

Types of Digital Technologies

The present paper distinguishes four broad categories of digital tools for smallholder LMIC farmers, clustering them on the basis of what they provide or facilitate. While this typology is offered to represent the major current and developing applications of digital technology in the context of smallholder LMIC agriculture, there are different valid ways of categorizing digital tools (Box 6). The four categories of technology are ones providing or supporting: (1) production-related information and advice, and farm management services, including farm mechanization and automation services;[6] (2) financial access, encompassing tools that relate to savings, credit, payments and liquidity, insurance, and the distribution of subsidies; (3) market information and e-commerce services; and (4) supply chain efficiency and risk management, by enabling traceability, logistics, and risk monitoring.[7] These technologies rely on a potential fourth category: digital building blocks including farmer registries, accessible, georeferenced, and relatable agricultural datasets, and ICT hardware.

Box 6: Other typologies of digital tools in agriculture

Various typologies of digital tools in agriculture have been offered. For example, one study focused on Africa, groups digital technologies into four groups, based on what they provide (Abate et al. 2023). Those groups are: (1) market advisory and information services (digitally enabled tools to deliver market information and advisories as a means of addressing different forms of market and institutional failures, particularly asymmetric information and high transactions costs); (2) market linkages (Digital information-sharing tools to link farmers to suppliers of relevant farm inputs such as seeds or fertilizers; suppliers of production and machinery services such as tractors; or even to wholesalers/retailers); (3) agricultural financial services and transactions (digital services that facilitate market transactions and financial services, aimed at lowering transactions costs and risks, or at improving efficiency and accountability in market exchanges, or improving quality assurance and traceability of agricultural products); and (4) agricultural market data collection, crowdsourcing services, and big data (digital tools that can collect market data from farmers while also allowing interactions between farmers).

Another study focused on digital tools for livestock farmers in Kenya and India groups tools on the basis of how "smart" they are. It distinguishes: (1) "simple digital tools," providing generic information; (2) "smart digital tools," providing tailored information based on data entered by livestock keepers; (3) "smart digital tools," using data from sensors; (4) "digital tools for value chains," enabling the integration of value chain actors; and (5) "automated digital systems," which are coupled with robots, allowing for automation (Daum et al. 2022).

Another study, this one focused on high-income countries, breaks down digital agriculture technologies by value chain segment, highlighting the broad range of digital applications in use or development in these contexts (Hackfort et al. 2020). The segments are: (1) agricultural inputs (ranging from fintech and data-based insurance to genome-edited seeds); (2) farm operations (including precision agriculture equipment, farm robotics, machine sharing platforms, data-based agronomic advice, and farm management platforms); (3) primary commodity trading (digital market places); (4) food processing (including collaborative robotics and 3D food printing); (5) packaging (including smart packaging and 3D printing); (6) transportation (including quality sensors and analytics, digital freight management, and digital transportation logistics for small-scale producers); (7) storage (automated warehouse); (8) retail and consumption (smart shopping and e-commerce); and (9) entire commodity chain (traceability and transparency tools).

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[6] This category includes all of the categories identified by Daum et al. 2022 except for digital tools for value chains (4). It also largely includes some of the big data tools identified by Abate et al. 2023 (4)—see Box 6.
[7] Note that risk management services are also included under the first category on information (e.g., in the form of early warning systems and advisories) and the second categories on financial access (e.g. in the form of savings and insurance services).

> The GSMA distinguishes: (1) digitial advisory, (2) agri-digital financial services, (3) digital procurement, (4) agri e-commerce, and (5) smart farming.

(1)Information, Advisory, and Farm Management Services (Production-Related, includes Farm Mechanization/Automation)

E-Learning and Extension Services: Organizations and governments are using digital platforms to provide training and extension services to farmers. "Digital Green" in India, Ghana, Nigeria, India, Kenya, and other countries uses videos and smartphones for knowledge sharing. Arifu in Keyna (in partnership with Syngenta) provides mobile-based agronomic advice to farmers. The China National Agricultural Technology Extension and Service Center (NATESC) operates various digital platforms to provide agricultural extension services, disseminate information on modern farming techniques, and offer advisory services to farmers across China. Several provinces of China have created online extension platforms. Digital products developed by IRRI include Rice Crop Manager, RiceAdvice, Rice Crop Calendar, iRiCE, SMARTSeeds app, (and the GRiSP science/knowledge management portal). In India, Vistaar is supporting extension workers and more with artificial intelligence (AI) and connected data sources.

Peer-to-peer and crowdsourced advice. WeChat, one of China's most popular messaging and social media platforms, hosts numerous agricultural services. These services include information sharing, advisory services, and group discussions where farmers can exchange knowledge.

Weather Information Services: Access to real-time weather forecasts and climate information through platforms like "WeFarm" and "Farmers Weather" helps farmers make informed decisions about planting and harvesting times. IRRI's RiceAdvice. Ignitia in Ghana sends out weather forescasts to farmers to aid in decision-making. Along with market information, Esoko provides weather information linked to agronomic advice.

Policy-oriented data platforms: KUADP is an online platform developed by the Kenyan Agriculture Transformation Office to consolidate fragmented data sources and address data quality issues to enable data-driven decision-making in the agricultural sector, including by farmers and policymakers.

Soil Testing and Fertilizer Recommendations: Mobile apps and devices are used for on-site soil testing, allowing farmers to receive customized fertilizer recommendations. "SoilCares" is one such company providing such services.

Mobile Apps for Crop Management (including pest and disease management): Various mobile applications have been developed to help farmers with crop management, pest and disease identification, and weather forecasting. Examples include "M-Farm" in Kenya and "Plantix" in India, which provide information and solutions tailored to local conditions. Tumaini uses AI to diagnose diseases from pictures uploaded by farmers in DRC, Uganda, Southern India.

Farm Management Software: Various farm management software solutions, such as "FarmLogs" in the United States, are also used in some Asian and African countries to track expenses, yields, and other farm-related data.

Crop Monitoring with Remote Sensing and AI: Satellite imagery and remote sensing technologies are used to monitor crop health and provide insights on irrigation needs and pest outbreaks. Companies like "Satsure" in India offer such services. In some cases, they are being enhanced by machine learning and AI, as in the case of Pole Digital Agricole (Morocco).

Automation and roboticization: semi-automated technology like assisted steering, roboticization of weeding, picking, spraying, and other tasks.

Precision Agriculture Technologies: Precision agriculture tools like GPS-guided tractors and drones are used in countries like China and the United States to optimize planting, harvesting, and pesticide application. Examples: In China, Aero Aggregates (XAG) specializes in agricultural drones and precision farming technologies for crop monitoring, pest control, and precision spraying);

Tencent provides IoT sensors, AI, and big data analytics for precision farming. Other examples: TROTRO Tractor in Benin, Ghana, Nigeria, Togo, Zimbabwe, and Zambia; Igara Tea in Uganda; ICT4BXW in Rwanda bananas.

Agricultural IoT Sensors: IoT sensors are used for monitoring soil moisture, temperature, and other environmental factors. These sensors provide data to farmers through smartphone apps, helping them make irrigation decisions. Examples: MimosaTEK in Vietnam, SatSure and CropIn in India, AgroCares in Kenya and other African countries.

Technology innovation support programs. In Tanzania and Kenya, mLab East Africa has supported initiatives and startups working on agricultural technology, including soil health monitoring tools.

(2)Financial Access (including commercial and government subsidies)

Mobile payments: Many smallholder farmers use mobile payment platforms like M-Pesa in Kenya and GCash in the Philippines to receive payments for their produce, access financial services, and make transactions.

E-banking / Digital Financial Services: Farmers can access credit and insurance services through digital platforms. In Kenya, FarmDrive enables farmers to borrow by risk profiling them using various sources of data; and "Branch" provides small loans to farmers based on their mobile phone usage data. In Rwanda, the government and Bank of Kigali partnered to register 1.5 million farmers to access agricultural finance using a digital farmer registry (includes farm location, crops grown, other farmer information). In China, Ant Financial, an affiliate of Alibaba Group, offers various financial services to rural communities. This includes digital lending, insurance, and financial tools designed to meet the specific needs of farmers. In Mali and Uganda, Oko provides agricultural insurance. In Kenya, Musoni microfinance uses data to extend financial solutions.

Peer-to-peer. In Indonesia, CrowdE enables peer-to-peer lending and finance. Agrikaab (formerly Ari.farm) in Somalia and Kenya is an online platform that aimed to crowdsource donations/investments in East African livestock and other farming activities.

e-vouchers and e-wallets (to allocate input and other government subsidies): Zambia launched an integrated agricultural data platform to support its farmer e-subsidy program. The Kenyan government's e-voucher system enables smallholder farmers to access agricultural inputs using digital vouchers.

Risk estimation. In India, Satsure has explored the use of remote sensing, machine learning, and artificial intelligence to offer financial institutions credit and insurance risk estimation or scoring services.

(3)Market Information and e-commerce

Market price information. Esoko in Ghana, Nigeria, Kenya, India, and other countries provides farmers with SMS-based information on market prices (as well as weather forecasts and agricultural advice). It has over 1 million registered users. In Kenya, KAZNET uses crowdsourcing to deliver high-resolution, near real-time livestock market data.

e-commerce (for agri-outputs): Examples: Rice Exchange (Ricex) enables farmers to sell their rice directly to international buyers, expanding market access and improving price transparency. "Agriculture Market Information System (AgMIS)" in India and "eKilimo" (developed by Mastercard) in Tanzania connect farmers directly with buyers, helping them obtain better prices for their crops. China has at least two agri ecommerce platforms that have achieved particular scale: Alibaba's Rural Taobao, which helps rural areas organize small "clusters" (Taobao villages) to sell online, and Pinduoduo, which enables farmers to sell agricultural produce in bulk directly to consumers by leveraging social media and cutting out intermediaries. Still in China, Meicai is a startup platform trying to facilitate the sourcing and distribution of fresh produce, connecting farmers with restaurants and retailers. Dada Now, a subsidiary of Dada Group, provides on-demand delivery services, including the delivery of groceries and fresh produce sourced directly from farmers. TaniHub in

Indonesia connects farmers to buyers including retailers, restaurants, and individual consumers and also offers logistical and quality assurance support. In India, Farmex integrates services ranging from advice and market information to financial and market linkage ones; Kisan Suvidha is another integrated platform for farmers. In Kenya, Twiga Foods is a mobile-based platform linking fruit and vegetable farmers to small and medium sized vendors, outlets, and kiosks in Nairobi and urban area; it is integrated with mobile money. In Kenya, Sokopepe is a internet- and mobile-based platform facilitating commodity trading by providing updated information about the price of commodities together with the geolocation of storage facilities, input suppliers, and extension services providers.

e-commerce (for agri-inputs): BigHaat is an e-commerce platform that connects farmers with suppliers of a wide range of agricultural inputs.

Land transfer and brokerage: The China National Agriculture Means of Production Group (CNAMPG), a state-owned enterprise, has been involved in initiatives to facilitate the transfer of agricultural land rights, and it operates digital platforms to streamline land leasing processes. In China, Tuliu facilitates agricultural land transfer and brokerage.

Farm employment platforms. There are app-based platforms that connect farmers and agricultural laborers and enable them to communicate and coordinate. Examples: Gainr in India and eFarmers in Nigeria.

Equipment sharing. Digital platforms facilitating the "Uberization" (that is sharing and rental) of farm equipment. Examples: Hello Tractor in Nigeria, Kenya, India, and China; EM3 AgriServices in India; and e-Krishi Yantra, an initiative of the Government of Madhya Pradesh in India; TROTRO Tractor in Benin, Ghana, Nigeria, Togo, Zimbabwe, and Zambia; and Tun Yat in Myanmar.

Digital Marketing and Sales: digital marketing and sales – market research and promotion

Soil carbon and other carbon monitoring. Boomitra is a project that aims to provide soil information and maps in Eastern Africa.

(4)Supply chain efficiency and risk management (traceability, logistics, risk monitoring)

Integrated marketing support services offered by e-commerce platforms. A number of e-commerce platforms, including Taobao in China and TaniHub in Indonesia offer support with marketing, including with packaging, logistics and shipping, and quality assurance.

Quality Control and Assurance Monitoring: Digitization enables real-time monitoring of product quality and safety. Quality control specialists are responsible for ensuring that food products meet regulatory standards and consumer expectations. In South Africa, Phytclean is an electronic digital platform that was developed by the government together with fruit growers' associations to capture, store, and report phytosanitary certification data for export-oriented products.

Warehouse and Inventory Management: With the implementation of digital inventory management systems, there is a growing need for professionals who can efficiently manage warehouses and ensure accurate inventory tracking.

Logistics Coordination: As digital technologies to enhance route planning, tracking, and transportation management.

Inventory and Demand management: Demand forecasting and inventory management are made more accurate and efficient through digital tools.

Cold Chain Monitoring: The digitization of cold chain systems

Supply Chain Traceability: In Ghana, Farmerline provides traceability, farmer profiling, certification tracking, farm mapping, input distribution, and advisory services. It allows users to track produce from farm to market using barcodes. In some cases, blockchain technology is being used to provide transparency and traceability in the rice supply chain, including to ensure fair prices and combat fraud. Examples: IBM Food Trust and PT Kotiva in Indonesia.

Disease monitoring and early warning. Big data is increasingly being used to monitor animal health, supporting early detection of animal disease, and preventing or minimizing adverse health impacts.

More Examples of Digital Technologies Supporting LMIC Farmers

Video-Based Extension: The Case of Digital Green in India and Ethiopia

In Ethiopia and certain Indian States (Andhra Pradesh), the use of videos featuring peers, a model developed by Digital Green, has been mainstreamed and received significant public support. The approach is touted as offering several advantages. First, it offers a means of reaching more farmers with extension messages with tight extension budgets. Second, videos of peers speaking farmers' own language are expected to be particularly compelling and convincing, leading to greater levels of adoption. The latter are expected to also be helpful in reaching women farmers.

One study that synthesizes the results of multiple rigorous evaluations of Digital Green and video-based extension finds mixed results in terms of increases in knowledge, adoption of practices, yield, output, gender effects, and community spillovers (IDinsights 2017). There were some small yet significant positive effects on knowledge, adoption, and yields, but these effects became more effaced by year 2 (in comparison to control groups, which were seemingly exposed to tradition extension messages). The studies do not seem to address the likelihood of being exposed to extension messages in the first place, although some studies make estimates about the cost-savings offered by the video-mediated approach. That said, the estimates are based on small studies and may be inflated.

The study concludes: "we see consistent achievements in the use of VMA to enhance near-term extension outcomes. VMA significantly increases farmer knowledge and adoption of new technologies in India and Ethiopia (Baul et al. 2020, Abate et al. 2019), and can positively influence womens' agricultural decision making in the household (Abate et al. 2019). A number of studies suggest higher adoption also translates to improved farm productivity (Baul et al. 2020, Abate et al. 2019, Campenhout et al. 2020), though the evidence is less robust for this outcome area."

Ethiopia's 8028 Farmer Hotline

Ethiopia's 8028 Farmer Hotline was developed by the government of Ethiopia 's Agricultural Transformation Agency (ATA) to provide farmers with real-time access to key agronomic information and help them make more informed farming decisions. Smallholder farmers access the hotline by calling the short code 8028. When they do, they are immediately sent advisories on good agricultural practices on all major cereal, pulses, and high-value crops. Farmers can register and set their preferences to receive information that aligns with their specific crops and topics of interest and geographic location, in the language of their choice (choosing from five language options). The hotline has broadcast more than 2 million alerts, many on the occurrence and treatment of crop diseases. Using the helpdesk function, farmers can also directly communicate with development agents in their woreda (locality) to report issues and ask questions.

Twiga Foods

In Kenya, Twiga Foods, is utilizing a mobile-based business-to-business (B2B) platform that is disintermediating and streamlining the flow fresh produce to urban markets by connecting smallholder farmers directly to small- and medium-sized vendors, outlets, and kiosks (most of them micro and small enterprises). Orders are taken and aggregated via a mobile app, and fulfilled within 24 hours. Commodities undergo stringent quality checks at aggregation centers before being transported to warehouses. The app is cashless and ensures farm to market traceability. Twiga also provides the MSMEs it works with business training and credit.

Farm.ink

In Kenya, Farm.ink set out to create a tool for farmers to sell their produce and get access to high quality agronomy training; the training aspect is what worked. The technology is meant to "load super fast on low-end smartphones." The startup is strongly committed to user-centered design.

Precision Agriculture Using Sensors

In Vietnam, MimosaTEK is a startup that is leveraging the Internet of Things (IoT) technology to develop precision agriculture in rice farming. Their service allows farmers to remotely monitor and control various aspects of their farming operations, including soil moisture levels, weather conditions, and water usage. The data is collected by sensors and transmitted to the cloud, where it is analyzed to provide real-time recommendations for farmers to help them determine the best time to irrigate and the optimal amount of water to apply.

In India, SatSure uses remote sensing, machine learning, and artificial intelligence to offer a range of agricultural services, from precision farm advisory/management (optimal planting times, irrigation scheduling, and other agronomic practices), to credit and insurance risk estimation or scoring for financial institutions.

CropIn offers solutions for precision farming, including soil health monitoring.

The Dutch AgroCares agtech company with a presence in Kenya and multiple partners across Africa, is offering soil testing solutions using "lab in a box" kits and hand-held digital scanners which are used in combination with its SoilCares, LeafCares, and FeedCares apps, which convert collected data into insights and advice.

Digital Platforms Bundling advice, market Information or E-Commerce, and Financial Services

TaniHub in Indonesia is an online marketplace that connects farmers to buyers including retailers, restaurants, and individual consumers and also offers logistical and quality assurance support. Through an app, it aims to establish direct links between crop producers and buyers, eliminating the need for multiple traders. It also enables parties to formalize last-mile procurement. The app secures a fair price and reliable payment service while also cutting the cost of a buyer's internal marketing or sourcing team. Buyers include commodity buyers seeking to supplement procurement volumes, supermarket chains, and hotels. TaniHub also operates TaniXpress, its logistics service, to collect and distribute crops across a network of producers and buyers. TaniFund, the lending platform, invites lenders to invest in agricultural programmes to meet capital requirements for marketing and selling agricultural produce, or to fund the establishment of new plantations. To date, TaniHub has helped more than 17,000 farmers sell their crops on its digital marketplace by listing over 60 kinds of fresh produce and over 60 institutional buyers.

In India, Farmex, a platform developed by eKutir, enables "digitally trained agro-entrepreneurs" to support groups of smallholder farmers access soil testing, fertilizers, pesticides, seeds, farming advice, and output markets. The agro-entrepreneurs are selected from among eKutir's farmer collectives, hired, and trained by eKutir. They are trained in entrepreneurship, social business, soil testing, seed supply, linking buyers to markets, and daily market price collection. They are also trained to use Farmex to facilitate, manage, and monitor a variety of data and transactions. Each agro-entreprneur can manage up to 200 farmers. Farmex also identifies the carbon emissions and footprint of each farmer through its FIX Carbon initiative.

Azure Data Manager for Agriculture (ADMA) (formerly Azure FarmBeats) – under development. The Azure FarmBeats platform was born out of a Microsoft research project. Launched in 2014, the FarmBeats project aimed to use AI, cloud computing, satellite imagery, sensors, and a variety of other digital technologies (including ones adapted to low-internet-access areas) to issue advice to farmers and enable data-driven farming decisions (for example on when to plant or use pesticides). According to Microsoft, the platform has stimulated innovation addressing a host of constraints to digital agriculture in LMIC contexts. For example, the project developed a way to use unused TV channels to send and receive data in poorly connected areas. Other innovations addressed challenges sending and receiving large volumes of data, or making use of satellite imagery in cloudy conditions. Microsoft 4Afrika partnered with the International Finance Corporation to build KuzaBot, a mobile chat platform intended to provide farmers rapid access to farming advice via WhatsApp and SMS. The chatbot has been criticized for trying to unduly influence farmers' input

purchases and generate business for large agribusiness corporations. The platform has also been criticized for providing farmers' information to commercially interested players (including information that can be used to risk-profile or market to them).

In Kenya, DigiFarm is an integrated mobile platform that facilitates farmers' access to financial and credit services, farming products, farming advice, market information, and market linkages (CGIAR 2021). The platform includes a chatbot service, Arifu, which reportedly provides them advice, promotes inputs and crop insurance, directs them to credit and financial service providers, and and directs them to product offtakers. The platform leverages the mobile money transfer service, M-PESA, to enable on-platform transactions. Safaricom, the subsidiary of Vodaphone which operates the Digifarm platform, charges a fee on all transactions. The platform has been criticized for unduly influencing farmers' purchases and financial decisions for the benefit of commercial service providers.

Financial Services

In Kenya, FarmDrive uses mobile technology and analytics to assess farmers' risk profiles (Deichmann et al. 2016; GSMA 2018b in Das and Landani 2020). Their risk profile draws on multiple sources of data including satellite images, weather forecasts, and data from buyers, agricultural dealers, and farmers themselves. Farmers register by sending an SMS. Financial institutions can use the risk profile to approve loans, which are disbursed via M-Pesa, Kenya's ubiquitous money transfer service (Robb and Vilakazi 2015 in Das and Landani 2020). This technology has been particularly helpful to unlocking financial access for women (GSMA 2018b in Das and Landani 2020).

Oko offers index insurance (for drought and flood risk) to maize farmers in Mali and barley farmer in Uganda. Farmers register for the service via mobile phones by providing their location, phone number, and crop information. Payouts are determined using satellite-based rainfall data. Oko's business partners include Orange and Allianz Insurance Group.

Musoni Microfinance is a cashless microfinance institution (MFI) that aims to give farmers in Kenya, including women and youth, access to financial services. Its Kilimo Booster loan product for farmers was designed in partnership with the Grameen Foundation. Musoni's loan officers collect loan applications and farmer data using a digital field application (DFA). The DFA is integrated with the core banking system through a web portal accessible by staff at the branch who can review and approve loan applications initiated in the field.

CrowdE is a digital startup based in Indonesia that enables peer-to-peer (P2P) lending and market linkages for farmers. It provides farmers with access to capital (up to IDR 100 million, or about US$6,500) backed by crowdsourced investors and distributed to approved farmers via its cashless network (World Bank 2023). The capital can be used for high-quality inputs, labor, access to production facilities or to finance other farming needs. CrowdE also connects farmers with distributors and agents to sell their extra crops. The platform has distributed loans to more than 17,000 farmers since its inception.

Traceability Systems Leveraging Blockchain

IBM Food Trust aims to enable end-to-end traceability in the food supply chain, by giving supply chain actors (including farmers, processors, distributors, retailers, and consumers) can access to a transparent and immutable record of a product's history. The platform utilizes blockchain, a distributed (decentralized) ledger technology, to create a secure and tamper-resistant records of transactions. It is meant to capture information about product origins, certifications, inspections, and sales. Information about products is available by scanning QR codes. It seems that is has mainly been used in high-income countries and/or with sophisticated large-scale producers including in India, Thailand, South Africa. The technology has been used to trace perishable and nonperishable items including fresh produce, meat, seafood, and dairy products, and grains.

PT Koltiva is an Indonesian agricultural technology company that offers digital traceability services to help farmers and other agricultural stakeholders track their products from farm to market. These

services help ensure compliance with food safety and other standards, and general transparency and accountability in the supply chain. Koltiva's multicrop KoltiTrace platform has been used in cocoa, coffee, and palm oil supply chains. The service uses a combination of technologies, including mobile apps, sensors, and blockchain to capture data at various stages of the supply chain and provide real-time tracking and monitoring.