Toward a Just Transition *in an Age of AgTech*

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

World Business Council for Sustainable Development

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Foreword

A Just Transition, as defined by Tackling Inequality: An agenda for business action from the Business Commission to Tackle Inequality (BCTI), "is *acting in line with science to address the climate emergency and restore nature, while leveraging these transformations to advance shared prosperity."* The agricultural sector employs over 800 million people worldwide[1] and provides livelihoods for 3.84 billion people, yet two of three people living in poverty are food growers, making the need to advance shared prosperity both urgent and essential.

A transformation of the agrifood system is underway and its role in building a net-zero and nature-positive world is gaining recognition. On the supply side, this recognition is driving a desire to better understand and mitigate the risks that stand before workers and suppliers, and leverage the transition to foster positive socioeconomic outcomes for farmers, rural workers and communities, as outlined in a 2023 WBCSD Insight.

A core element of a just transition is workforce evolution – one of the four pillars of the Council for Inclusive Capitalism's Just Transition (JT) Framework for Company Action. The principle is that a company's workforce must have upskilling opportunities and be empowered to benefit from the developments transforming the world of work (BCTI Action Agenda 4).

With the food systems transformation well underway, a resurgence of interest in technology-based solutions can contribute to accelerating actual technological change. In this context, mechanization and digitization have the potential to boost farmer livelihoods – a key pillar of WBCSD's Food and Agriculture Roadmap – – mitigate risks and make agricultural labor more attractive. Furthermore, as agricultural machinery and technology become more sophisticated, a corresponding upskilling of rural labor could potentially lead to increased job stability.

However, technological change often comes with unintended consequences, particularly in interaction with existing vulnerabilities and the inequities present in food systems. In the case of mechanization and digitization, concerns surround their potential to sideline the most asset-poor farm workers from agricultural development dynamics and exacerbate the work-related hardships they face. Such a shift could potentially leave the most vulnerable unprepared for the future of agricultural work. Because so many livelihoods depend on food systems, in 2023, the Just Rural Transition developed a set of Principles of Just Food Systems Transitions to help guide business and other actors in implementing change processes that can benefit climate, nature and people simultaneously.

Going a step further, this paper aims to help business anticipate and mitigate the potential unintended consequences of the technological transition by answering two questions:

- What will the effects of this transition be on the livelihoods and working conditions of smallholder farmers and other agricultural workers in low- and middle-income countries?
- What measures have and can business take to better spread the benefits of technological change and better mitigate associated risks?

With this paper, we aim to provide a framework for thinking about how the technological dimensions of the food systems transformation can facilitate better work conditions within the sector, enabling fit-for-future jobs, adequate supply, livelihood-resilience and prosperity.

[1] In primary agricultural production.

Executive Summary

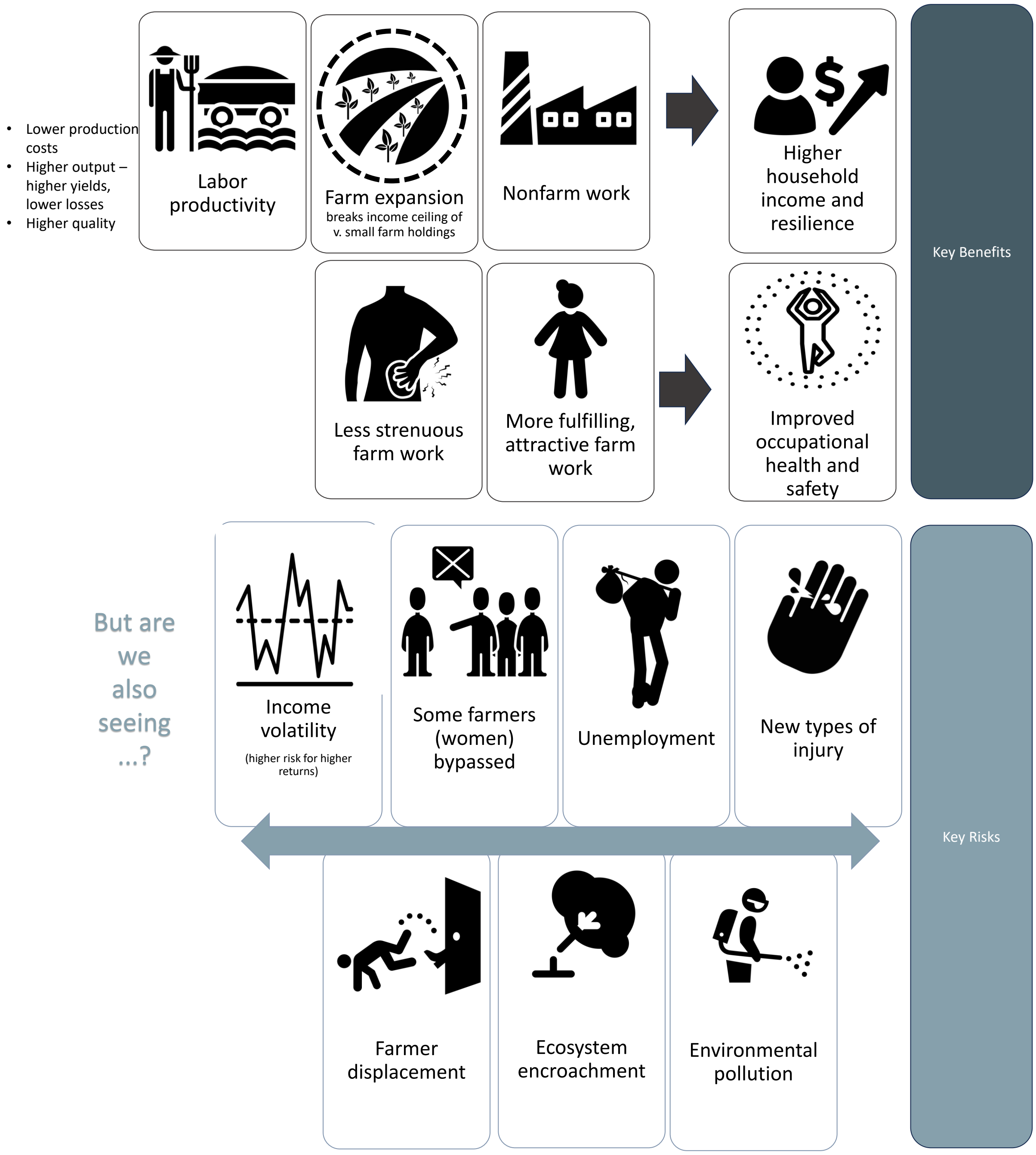
Globally and in lower- and middle-income countries (LMICs), a food systems transformation is underway. This transformation is being driven in part by socioeconomic, climatic and other realities and trends, as well as a range of societal aspirations – notably those of nourishing the planet while decarbonizing the economy and remaining within planetary boundaries. In this context, a resurgence of interest in technology-based solutions and the possible acceleration of technological change raise the question of how technological change may affect the inclusiveness of the food systems transformation. In what ways will the trends of mechanization and digitization support a just transition within food systems, and in what ways may they unintentionally cause harm? What can business do to maximize and spread the benefits of technology adoption for LMIC farmers while mitigating potential risks?

Mechanization and digitization have the potential to be hugely beneficial, and at times, game changing for LMIC farmers addressing their key farm management, risk management, market access or income constraints. In the case of mechanization, much of its potential to benefit LMIC farmers has already been demonstrated at scale, although far more so in Asia than in the less-mechanized Africa. There is far less evidence substantiating the many expected benefits of digitization. However, concerns that the application of such technologies in LMIC agriculture will lead to highly inequitable outcomes do not appear to be supported by the available evidence, at least not in many parts of Asia and Africa. That said, technology adoption is not without risk, and both mechanization and digitization can have unintended consequences that warrant efforts to prevent or mitigate them.

Benefits and Risks of Mechanization

The widespread mechanization of small farms across major parts of Asia has demonstrated how motorized or "power" equipment can act as an income multiplier. Not only have they raised the productivity, output and ability for farms to create and add value, they have also allowed members of farming household to diversify beyond farming and overcome the income ceiling associated with very small land holdings. For small farming households growing staple foods like rice and maize, nonfarm employment may be the surest way of attaining a living income in contexts where decent nonfarm work can be found once members of farming households are able to free up some of their time. It can also make farmers more resilient to income fluctuations by raising their average incomes. From an occupational health and safety perspective, power equipment can help reduce the strain and drudgery of manual farm labor, but also introduce new risks of injury, at least until safety features and precautions are introduced to mitigate them. **Error! Not a valid bookmark self-reference.** illustrates the major ways in which mechanization has demonstrated that it can improve farmers' incomes, resilience and working conditions, while also flagging what can go wrong. For example, in settings where land is scarce and land tenure weak, mechanization-induced farm expansion and consolidation have been known to displace more vulnerable farmers.

Figure 1: How Mechanization Can Improve Farmer Incomes, Resilience and Working Conditions, and Risks to Be Aware Of



Benefits and Risks of Digitization

Digital technologies are widely expected to improve the performance and incomes of small farmers. Digitization is expected to increase farmers' productivity and incomes by, among other things, increasing their access to relevant information, knowledge and advice, including how to manage risk, obtain higher yields and grow higher-value crops in a changing climate. It is also expected to increase their access to finance, productive inputs and equipment, while improving the input and output prices they obtain. By opening up the possibility of automation, digitization (in combination with mechanization) also has the potential to help improve the efficiency, safety and attractiveness of farming. While digitization could conceivably be used against farm workers to monitor them in plantation or other salaried work contexts, the hope is that digital tools will enhance the efficacy of efforts to combat human trafficking and abusive practices in agricultural supply chains.

However, empirical evidence supporting these benefits remains thin, and while that partly reflects the relative novelty of digitization, it may also reflect its relative ineffectiveness. Most of the empirical evidence on digitization is derived from evaluations of small-scale projects and experiments, most of which relate to information and advisory tools. It may be too soon to tell, or it may be the case that many pilots have not scaled up because they have underperformed. Empirical evidence suggests that digital solutions can be beneficial but have not been a panacea to date. Moreover, mismatches between farmer needs and what technologies offer are common.

Digital technologies also potentially pose several other risks, most of them prospective. A scenario in which digital technologies could harm farmers is one where digital platforms' bundling or offering access to multiple services facilitate the accumulation of market power and its use to undermine market competition. While digital platforms and services may have particular value to farmers, including bundling a multiplicity of services, they may be subject to "lock-in" effects.

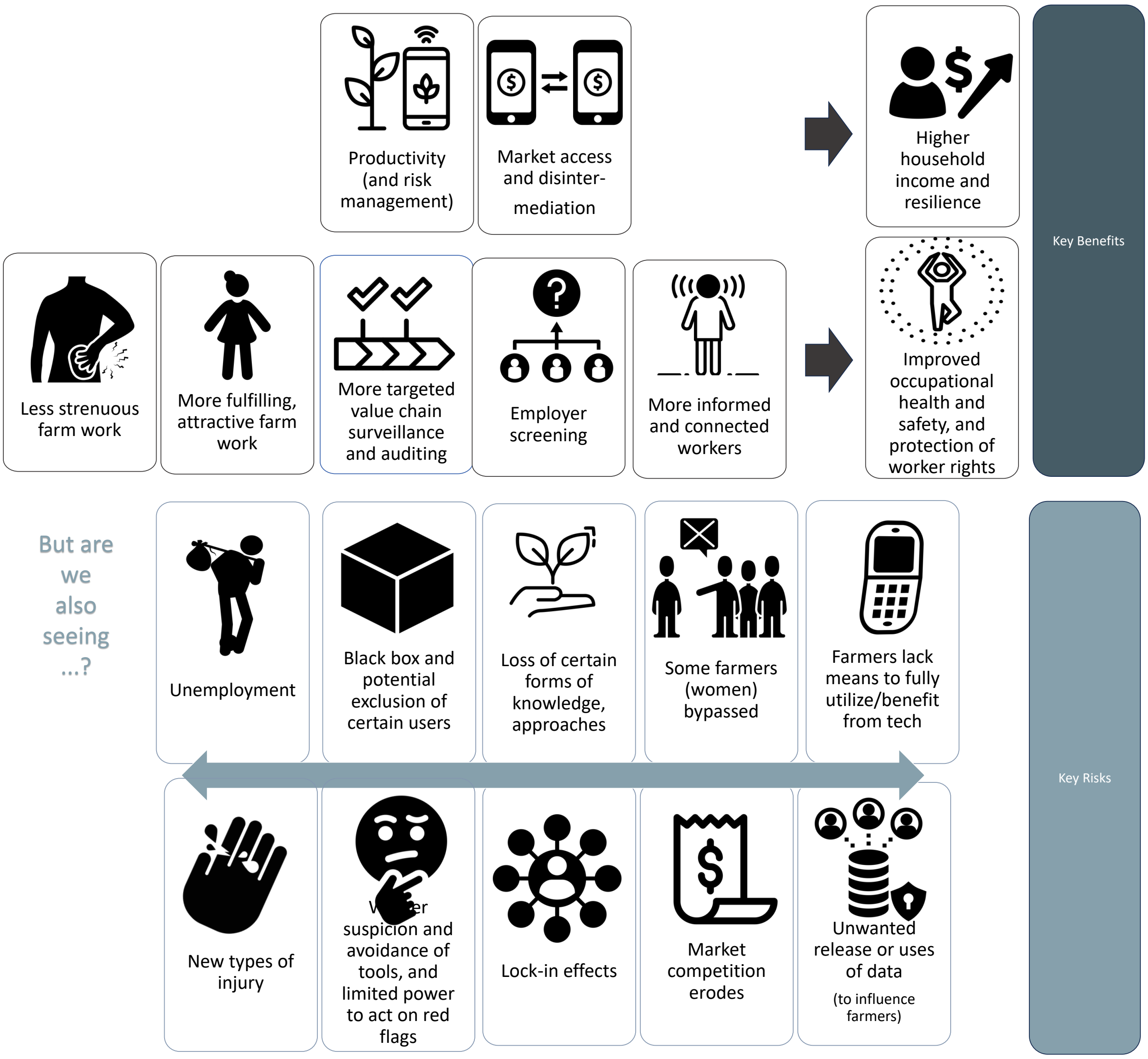
Another unintended risk scenario is one where user data (released knowingly or unknowingly) is used to influence or narrow farmers' choices in unwanted ways. If creating transparency is one of the key ways digital technologies can empower farmers – by helping them discover market prices and preferences – those that deploy opaque and powerful analytic tools can have the opposite effect. To provide a concrete hypothetical example of this, a digital risk profiling system may allow an unbanked female farmer without a land title to access credit for the first time, but if the risk profile is erroneous for an unexplained reason, or prone to systematic biases, the same system could also shut that woman out of the credit market with little or no recourse. Figure 2 illustrates the major ways in which digitization is expected to improve farmer incomes, resilience and working conditions, while also flagging what could go wrong.

Spreading the Benefits of Technology while Mitigating its Risks

Meanwhile, as already illustrated in the figures above, the main risk associated with both mechanization and digitization is almost certainly that of non-adoption. Because both families of technology have the potential to be game-changing, not having access to them can drive a wedge between adopters and nonadopters, particularly in contexts where some adoption is occurring. It is also often the case that the smallest of small farms find it harder to adopt farm machinery, with less land to collateralize for credit and generate returns from. It is also the case that women often have limited access to either class of technology. In some contexts, the farming tasks performed by women are bypassed by mechanization or have been the last to mechanize. And women have been underrepresented in the use of some of the major digital platforms emerging to offer farmers extension, advisory, data, marketing and financial services, among others.

From this perspective, a range of public-interest investments, policies and programs have the potential to help spread the benefits of technology more widely by helping to facilitate market-led adoption. To support mechanization, public-interest actors can invest in roads and energy infrastructure, support R&D and help address credit market failures. Even though equipment manufacturing is not a prerequisite for mechanization in countries seeing widespread adoption, the public sector can help by sharing costs and orienting R&D to adapt tools to local contexts and facilitate the local availability of parts and service – two key constraints to scale-up. In support of digitization, public-interest actors can invest in energy access and internet connectivity, some R&D, and conventional, financial and digital literacy among rural populations. In many countries, digital expectations have gotten ahead of and out of touch with the realities of farmers, and at times, the targeting of public or international investment has followed suit (that is, putting apps before the basics). Before expectations can materialize, the building blocks for a digital transformation need to be put in place in rural areas. More generally, public interest actors can help create conditions conducive to private sector innovation, including legal and regulatory ones, and reduce transaction costs.

Figure 2: How Digitization Can Improve Farmer Incomes, Resilience and Working Conditions, and Risks to Be Aware Of



In addition, some more targeted interventions may be warranted to support the mechanization and digitization of specific groups of farmers being left behind. In such instances, indirect forms of support may be best. For example, support for smallholder farmers' access to credit or capacity to organize among themselves may ultimately be more helpful than machinery subsidies or the direct rental of machines or related services. As Asia's experience demonstrates, governments can also play important, if circumspect, roles in fostering the emergence of competitive markets for machinery rental or mechanization services, which can be critical enablers of mechanization among the smallest of smallholders. Other interventions may be warranted to help more female farmers access and better benefit from technology by helping to change social norms and empowering them.

However, experience suggests that overly direct and aggressive support for mechanization is not necessarily a helpful, pro-poor use of resources. Non-adoption sometimes occurs for good reasons; notably, in contexts where there is an abundance of (unskilled rural) workers and a scarcity of nonfarm livelihood opportunities to engage in. When these circumstances coexist, mechanization is typically tempered by its economic inefficiency for all involved. Pushing mechanization prematurely has the potential to displace some of the poorest and most vulnerable farm workers (in some contexts, landless ones), at least until it fails due its lack of economic viability. While this may sound like a gloomy set of possible outcomes, the story is largely a positive one, since they seldom materialize.

Meanwhile, there are multiple avenues for guarding against the unintended consequences of technology adoption for farmers. For example, helping farmers secure their land rights can help guard against their displacement in a context of mechanization-driven farm consolidation or expansion. To ward off the risk of injury from farm equipment use, the public and private sectors can collaborate to develop and adopt things like safety standards, protocols and operator training and licensing. Regarding digitization, limitations in scale to date are not a reason for complacency in terms of the potential risks that might be associated with its upscaling.

A Framework for Context-Informed Action

For actors looking to help shape technology trajectories that are consistent with a just transition in LMIC agriculture, the best stance and set of actions to take is bound to vary across contexts. Just as contextual factors can influence technology adoption rates and associated opportunities and risks, they also inform the types of actions that will be most effective at spreading the benefits and mitigating the risks of technology.

While there are many relevant contextual factors, private sector action can be guided in relation to three distinct agrifood system settings: traditional, transitioning and modernizing. Typical of low-income, lower middle-income and upper middle-income countries, respectively, the three settings are associated with different stages of agrifood system transformation and levels of economic development. They also tend to be associated with substantially different opportunity and risk profiles with respect to agricultural mechanization and digitization. It follows that the focus, mix and modes of private sector action will and should differ across these contexts. Three modes of private sector action are described in Box 1. Bringing together the different contexts and modes of private sector intervention,

Figure **3** presents a framework for context-informed action.

Box 1: Three modes of private sector action

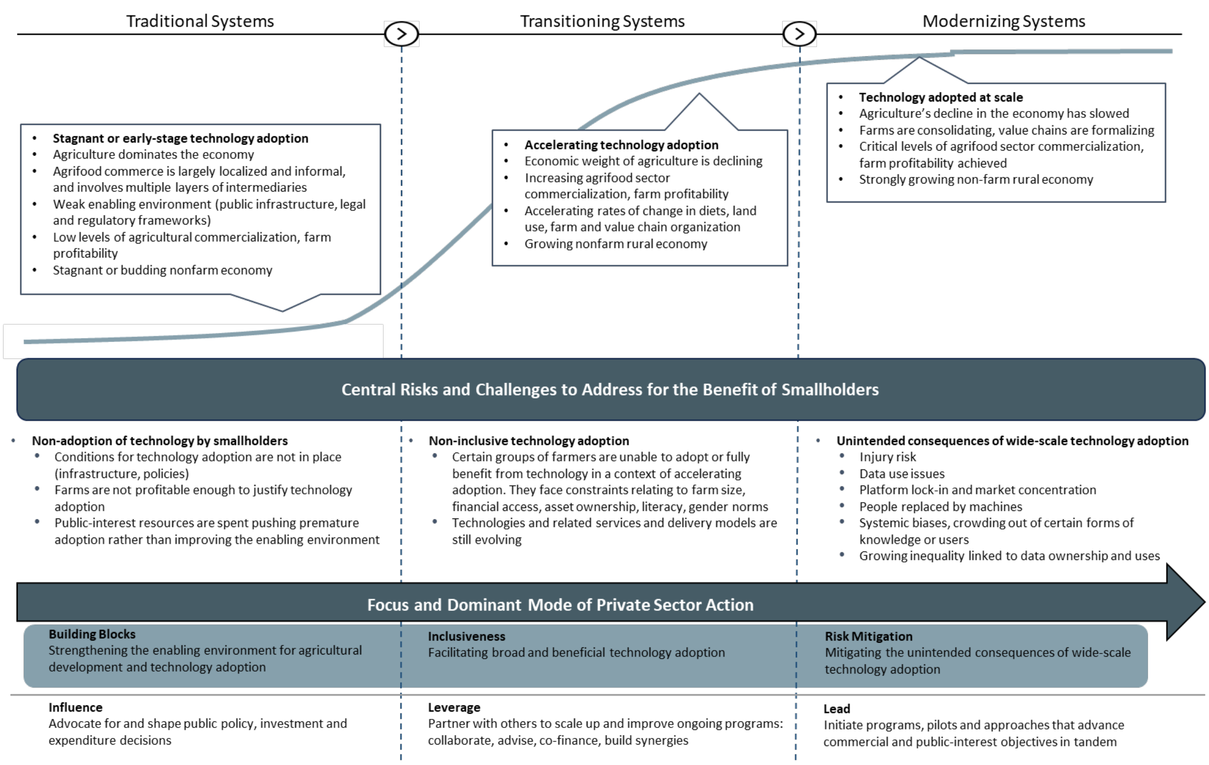
- ***Lead***: In this mode, the private sector directly invests, provides specific services and applies given business practices. In this case, the private sector may supply technology directly, or incorporate it into value chain operations.
- ***Leverage***: In this mode, the private sector works or partners with other stakeholders – like government entities, NGOs and development agencies – to scale up and improve ongoing programs. This mode may involve collaboration, advisory work, direct investment and co-financing.
- ***Influence***: In this mode, the private sector acts as an advocate and advisor, shaping public policy, investment and public expenditure decisions.

- In **traditional systems**, both agricultural commercialization and technology adoption are limited and the enabling conditions for both are relatively weak.
  - In these settings, the central focus is on **establishing the building blocks for market-led mechanization and digitization**. Doing so can involve investment in basic rural and agricultural infrastructure; the adoption and implementation of policies and regulations that support agricultural sector productivity, commercialization and development at large; and programs supporting early adopters of technology and service providers. Some commercial opportunities may be available, creating opportunities to demonstrate responsible business practices.
  - The scope for private sector action lies primarily in **influencing** and supporting efforts led by the public sector.

- In **transitioning systems**, many changes are occurring in agriculture and the wider economy, value chains are commercializing and formalizing and technology adoption tends to be accelerating.
  - In these settings, the central focus is on **supporting inclusive and effective technology adoption.** Doing so implies addressing financial, technical, social, institutional and other constraints to technology adoption, and paying particular attention to female farmers and others at risk of exclusion.
  - The scope for private action lies primarily in ***leveraging*** existing initiatives and engaging in joint efforts, including public-private ones.

- In **modernizing systems**, previous changes are consolidating and deepening. Agrifood systems are growing more complex, and typically, technology adoption has occurred at scale.
  - In these settings, the central focus is on **furthering commercial technology provision and using them with an increased focus on mitigating the unintended consequences of technology adoption.** Increasing attention can be paid to occupational health and safety and an array of digital risks, from anti-competitive practices to data use.
  - The scope for private sector action lies primarily in ***leading*** innovation and risk mitigation efforts.

Figure 3: Priority Private Sector Actions by Context



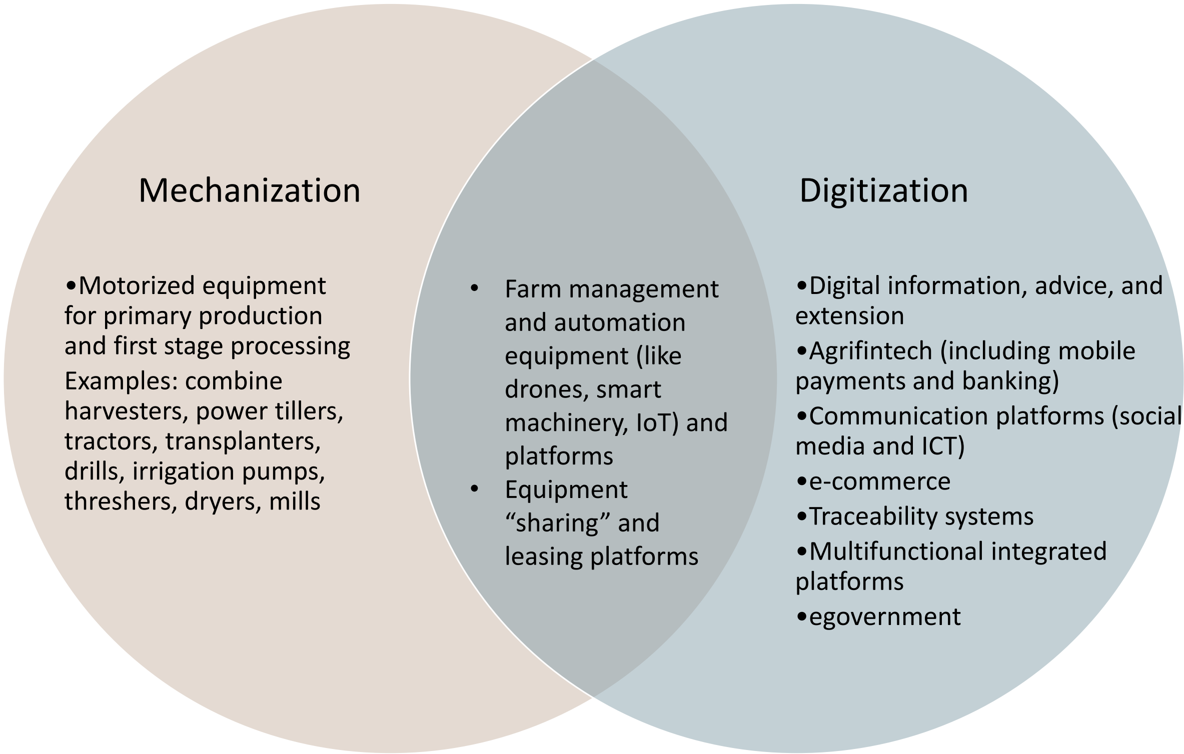
1. Introduction

Technology has always been a central driver of agricultural development, and today, much hope is invested in the contributions that mechanization and digitization can bring to solving one of the sector's, and the world's, central development challenges. By 2050, the agricultural sector will need to nourish 10 billion people in a warming and urbanizing world, while helping to restore and protect ecosystems and biodiversity, keeping the world within planetary boundaries and transitioning some 500 million smallholder farmers out of poverty. From the perspective of low- and middle-income countries (LMICs), where large numbers of poor small-scale farmers ("smallholders") produce the food that these populations consume and export, both hope and concern surround the potential for mechanization and digitization to support a just and inclusive transformation.

The mechanization of agriculture has in a sense been occurring for centuries, although in developing countries, it accelerated in the late 20th century during and after the Green Revolution. The Food and Agriculture Organization (FAO) defines agricultural mechanization as the application of tools, implements, machinery and equipment to achieve agricultural production. These include manual tools (like hand-operated and non-motorized pumps, plows, seeders and transplanters), animal-powered tools and motorized tools (like tractors and combine harvesters) (FAO 1981, FAO and AUC 2019). In recent decades, many LMICs have seen widespread adoption of such tools and equipment by smallholder farmers and others, often helped by a decline in technology costs and the availability of government subsidies, both for the developers and users of the technologies. Common machinery is used in land preparation, sowing and transplanting, irrigation, harvesting and on-farm processing (threshing, drying, milling, pulping, washing, fermentation, quality monitoring and sorting).

The digitization of agriculture involves the direct or indirect use of digital technologies and includes a rapidly evolving set of tools, systems and capabilities. These include but are not limited to hardware like internet equipment, mobile networks, phones, computers, radios, other ICT, drones, satellites and sensors, as well as a wide range of software and systems, including data management and analytics tools, cloud computing, machine learning, artificial intelligence (AI) and blockchain platforms. A latecomer to the digital economy, which itself is only roughly three to four decades old, the agricultural sector is now making up for lost time and rapidly exploring all that digital technologies can offer. In the context of small family farms in LMICs, dominant applications of digital technologies include agrifintech (including mobile payments and banking), digital extension and market information systems, communication platforms (including social media and ICT) and e-commerce (including leasing, sharing and direct-to-consumer platforms). While some farm automation is evident in small farms using digital technologies to enhance or shape new power equipment, it remains in early stages, given the technology originated in large-scale commercial farm systems. Figure 4 shows major agrifood sector applications of technology coinciding with the mechanization and digitization of technology in LMICs. A typology of mechanization and digitization technologies and examples thereof are included in Annex 5.

Figure 4: Major Agrifood Sector Applications of Technology Underlying Mechanization and Digitization in LMICs



Like earlier technological trends,[2] those associated with mechanization and digitization have considerable potential to modernize farming, and in turn, influence the nature, organization, profitability, environmental footprint, safety and attractiveness of farm work. With their capacity to enhance labor productivity, decrease transaction costs, reduce information asymmetries, enable more effective land and water utilization, improve product quality and enhance the "precision" of farming operations, among other things, there is an opportunity for ongoing mechanization and digitization to help boost farmer livelihoods, mitigate occupational and environmental risks, address gender and other inequities and attract youth to the sector. Many developing countries are now actively promoting the adoption of these technologies. Many results look promising, at least technically, yet there are questions about how the adoption of these technologies is impacting or will impact smallholder agriculture and the welfare of workers whose livelihoods depend upon it.

Yet, technological change often comes with unintended consequences – as well as limitations[3] – particularly when interacting with existing vulnerabilities. In the case of mechanization and digitization, concerns surround their potential to exclude the most asset-poor farm workers from agricultural development dynamics and exacerbate the work-related risks and hardships they face. Such unintended consequences are best mitigated when they are anticipated and well managed. As such, it is timely to take stock of recent experiences,

[2] Historically, several sets of technologies have had transformational effects on farming. For example, this was the case of improved seeds and animal breeds, and an enormous amount of literature has examined the drivers, patterns and effects of their adoption. That topic is well understood and therefore not within the scope of this paper. Much less well-understood are the effects of mechanization and digitization on smallholder farming and the workers it supports.

[3] A companion question is that of technology's limitations. For instance, the rate at which former farmers find employment in emerging occupations in the tech economy can be limited by a mismatch in skills, location and number of available jobs. These outcomes are not directly caused by mechanization and digitization, but suggest that their contributions to economic restructuring may not benefit all workers.

what the evidence tells us about the evident opportunities and risks associated with the adoption of these technologies within smallholder agriculture and draw attention to policy and program interventions that have or could lead to better outcomes and trajectories.

This paper is specifically focused on the implications of mechanization and digitization for farmers in Sub-Saharan Africa and Asia.[4] Its central purpose is to help commercial agrifood players think about the opportunities and risks associated with technological change in contexts where they are sourcing raw agricultural commodities. It further aims to offer insights and guidance on how business actors can ensure responsible sourcing in contexts of rapid technological change. Recognizing the strong potential benefits of technology from labor and other perspectives, the paper identifies roles the private sector can play to help ensure that technology delivers the best of what it has to offer and is consistent with a just transition.

Indeed, a key question that arises is whether and how mechanization and digitization in LMICs might facilitate inclusive agricultural development and a just transition. In this context, the latter refers to an agricultural development dynamic that would support nutritional health and environmental aspirations in ways that would widely benefit those remaining in the sector (including smallholders), leave no one behind (even if many leave the sector) and not exacerbate inequality (Box 2). If *all* the aforementioned promises of technology can be realized in tandem within smallholder agriculture, then perhaps many small-scale farms can have a viable and vibrant future, and the national agricultural systems in many LMICs can continue to transform in a relatively inclusive manner.

Box 2: Defining a "just transition" in LMIC agriculture[5]

According to the International Labor Organization (ILO), the concept of a "just transition" captures the idea of, "greening the economy in a way that is as fair and inclusive as possible for everyone concerned, creating decent work opportunities and leaving no one behind." Inspired by that understanding, a just transition in agriculture, as used in this paper, refers to a planned shift toward carbon neutral and nature-positive agricultural systems, which results in widely shared benefits and supports those who stand to lose economically or otherwise from both foreseen and unforeseen consequences of change. In the context of LMICs, the "just" quality of the transition is closely tied to how it affects the livelihoods and well-being of small, low-income farmers in LMICs, with women and landless farm workers often being the most disadvantaged among them. The concept of a just transition also precludes rampant and deepening inequality, especially of the most extreme kind.

According to a 2023 Just Rural Transition paper on the topic,[6] a just food system should:

- Meet the nutritional needs of all people while respecting planetary boundaries
- Provide good livelihoods through jobs and supply chains
- Protect people's rights and correct inequities
- Treat animals well
- Be resilient to climate change
- Stop and reverse environmental degradation.

[4] Less attention is paid to fragile and very low-income countries where the agricultural sector is relatively stagnant and demographic changes are occurring at a slow pace.
[5] Further guidance on just rural transition can be found in Principles for Just Food Systems Transitions and Preliminary Insights on a Just Transition in Agriculture produced by WBCSD in partnership with the Council for Inclusive Capitalism and PwC.
[6] https://justruraltransition.org/wp-content/uploads/sites/12/2023/04/JRT_Principles_Report_170423.pdf.

To consider how these forms of technological change might relate to a "just transition" in the context of LMIC agriculture, this paper asks the following set of subsidiary questions.

1. How do mechanization and digitization affect smallholder farming households and related farm workers, especially in terms of their productivity, incomes, working conditions and ability to work elsewhere as well?
2. How are these effects distributed? Who has the most to gain? Whose livelihoods are adversely affected or whose working conditions might worsen?
3. What are some critical factors or circumstances (market, institutional, socioeconomic, technology, policy, regulatory or other) that influence which effects play out or dominate, for whom and at what scale? And, which of these factors or circumstances are amenable to change? In other words, what interventions effectively help capture the opportunities and mitigate the risks associated with mechanization and digitization?

To answer these questions, this paper draws on available evidence on the effects of mechanization and digitization on LMIC farmers. Opportunities and risks are identified in relation to three broad outcomes. As shown in Figure 5 they are: (1) the ***incomes*** of smallholder farm households (both on and beyond their farms) and of those who are hired to work on these farms on a regular, irregular or seasonal basis; (2) the ***working conditions*** or non-income dimensions of work in smallholder farming systems, including occupational health and safety and work attractiveness; and (3) ***equity and inclusion***, which may be related to gender, age, asset-endowments and other factors. It is possible that mechanization and digitization at scale yield both winners and losers, as well as have others who are minimally affected. Across these dimensions, this paper is primarily concerned with the human dimensions of technology adoption, with a focus on smallholder farming households[7] and (associated) hired farm workers.[8]

Figure 5: Broad Outcomes of Interest

Most of the evidence examined comes from contexts where agricultural and technological transitions are in full swing. Some of these contexts are noted in Box 33. In keeping with this perspective, this paper does not attempt to answer why technology *adoption* is strong or weak in different contexts, but what happens when certain farmers are excluded from adoption dynamics. The paper also focuses almost exclusively on crop agriculture, with many of the examples drawn from applications of technology in two of Asia's key staple crop systems: rice and maize. It does not focus much on large-scale commercial or plantation agriculture. This scope helped facilitate a comparative analysis of enabling and disenabling factors. Annex 4 further elaborates on the paper's evidence basis.

[7]Smallholder households that have significantly adopted mechanized or digital solutions likely include those who are regularly supplying formal agricultural markets or value chains, and those who have secure and adequate land, adequate managerial capacity and finance.

[8] In some cases, a high proportion of work is done by workers who are not family members and are hired on a regular, irregular or seasonal basis.

Box 3: Examples of geographies where mechanization and digitization are strongly progressing and influencing farming activities and agricultural sector dynamics

- In Nigeria, rice farmers in states like Kebbi, Ebonyi and Kano are – with government encouragement – adopting transplanters, threshers and rice mills, and turning to digital platforms to obtain weather forecasts, agronomic advice (including when to plant and harvest, and how to prevent and manage pests) and market prices.
- In Ghana, small-scale cassava farmers are adopting mechanized cassava graters and processing machines and relying on digital platforms to connect to processing facilities and markets.
- In Kenya, small dairy farms are adopting milking machines and automated feeding systems, as well as digital apps to track animal health and milk production.
- China has been a leader in the mechanization of smallholder cereals production, with tens of millions of farmers having their land prepared, seeded, sprayed and/or harvested by hundreds of thousands of agricultural mechanization service companies. Online platforms are linking millions of farmers to markets.
- In the Indian "breadbasket" states of Punjab and Haryana, wheat, rice and industrial crop farmers – including small- and medium-sized farmers engaged in cooperative farming and machinery-sharing arrangements – are turning to GPS-guided tractors and transplanters, soil sensors, drones and precision equipment to optimize planting, irrigation and fertilization, and using digital platforms to obtain weather forecasts, advice and market information.
- In Vietnam's Mekong Delta, one of the rice baskets of Asia, small-scale farmers are adopting power tillers, combine harvesters and mechanized transplanters, and using digital tools to monitor crop and soil health, water usage and greenhouse gas emissions. Maize farmers in the midland regions of the country are adopting mini-tractors and maize shellers.

2. Findings

Drawing on available evidence, this paper's findings are organized around five (non-mutually exclusive) clusters of questions. These relate to: (1) smallholder farming household incomes; (2) the occupational health and safety and attractiveness of farm work; (3) hired farm worker employment, wages and working conditions; (4) differentiated effects on women and groups of farmers (on incomes and working conditions); and (5) prospective risks of digital platforms (for farmer incomes and income inequality). A summary of key opportunities, risks, red flags and enablers related to each of these dimensions is provided in Annex 2.

2.1 Smallholder Farming Household Incomes

How and to what extent have mechanization and digitization helped enhance the incomes of smallholder farming households? When and how have these technologies had unintended consequences?

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 can 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 to avoid catastrophic crop losses (by using information advice about impending risks, like extreme weather, and working around them).	• 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 to less competitive input and output prices.

Mechanization and digitization both have the potential to raise the incomes of smallholder farming households when technologies effectively address one or more of their income constraints, such as scarce and high-cost labor, a lack of knowledge or a lack of access to finance and markets. Furthermore, the positive effects of mechanization and digitization on incomes can be significant. In Zambia, one study found that the incomes of mechanized farming households were twice those of non-mechanized ones, after controlling for other factors (Adu-Bafour et al. 2019). In Nigeria, another study found that tractor use raised real incomes by 13% (Takeshima and Lawal 2020 in Daum 2023). One study of agricultural digitization in Africa found that digital technologies were associated with income improvements of 20-40% (Tsan et al. 2019). That said, some studies point to disappointing results. In Rwanda, for example, Grameen/MTN village phone had no effect on prices or profit (Futch and McIntosh 2009 in Abate et al. 2023).

A key way in which technology benefits farmer incomes is by increasing their labor productivity. Mechanization is known to achieve this in several ways.

One of them is by decreasing reliance on labor, which in some farming systems is a dominant component of production costs. In the words of rice scholars, “Reducing labor cost is one of the main ways to improve competitiveness and increase labor productivity so that rural incomes can increase over the long run” (Mataia et al. 2016). One major study compared the production systems and productivity of rice in six leading production zones in Asia. One important distinction was the degree of mechanization, especially for land preparation, seeding and harvesting. In three of the production zones – in China, Thailand and Vietnam – mechanization was very widespread, if not universal. In the other three, mechanization was either moderate (India) or very low (Philippines and Indonesia). High levels of mechanization resulted in a three to tenfold reduction in labor use per crop on a per hectare basis (Mataia at el. 2016).

In this comparative analysis, mechanization was found to be a major (yet not exclusive) factor explaining differences in labor productivity. This relationship is illustrated in Table 1 where labor-intensive areas (in Indonesia, India and the Philippines) and highly mechanized ones (in China, Vietnam and Thailand) are shown in differently shaded rows. Productivity differences are illustrated in two ways – by the monetary return ($) per person-day (net profit) and by the quantity of harvested paddy (kg) per person-day. The results make clear the enormous boost that mechanization has given labor productivity in several of the leading rice bowls.

Table 1: Labor Use and Labor Productivity in Asia’s Major Rice Bowls

Rice Bowl	Total Labor Use (Person-Days/Ha)	Net Returns Per Person-Day ($)	Grain Yield Per Person-Day (Kg)
Indonesia (West Java)	96	8.84	64
India (Tamil Nadu)	78	2.63	55
Philippines (Nueva Ecija)	69	10.53	83
China (Zhejiang)	35	20.86	214
Vietnam (Can Tho)	22	49.13	391
Thailand (SuphanBuri)	10	62.52	533

Source: Based on Mataia et al 2016. Note: Data shown is for the “high yielding” season. Labor intensive areas: Indonesia, India and the Philippines. Highly mechanized areas: China, Vietnam and Thailand.

Another way mechanization raises productivity is by increasing farm output and its value. It can do this by enabling farmland expansion, higher cropping intensity (crops grown per year), higher yields (land productivity) or less loss and damage.

Sometimes, mechanization allows an expansion of the cultivated area, leading to higher farm output. In some cases, it does so without increasing yields (Baudron et al. 2012; Berhane et al. 2020; Bishop-Sambrook 2005; Houssou and Chapoto 2015; Nin-Pratt and McBride 2014; Bhattarai et al. 2020; Pingali 2007 in Daum 2023). For farming households with very limited land holdings (in Asia, vast numbers of farmers have less than 2 ha), farm expansion can be the difference between economic viability and nonviability. Mechanization-enabled farm expansion has been observed, among other places, in

Indonesia (Yamauchi 2016 in Daum 2023), Brazil (de Oliveira et al. 2017 in Daum 2023), Nigeria (Takeshima and Lawal 2020 in Daum 2023), Zambia (Adu-Bafour in Daum 2023) and Ghana. In Ghana, one study found that tractor use was associated with a 14% increase in cultivated land (Houssou and Chapoto 2014 in Daum 2023); while another found that mechanization led farm sizes to double, from around 1 to 2 ha, within 10 years (Kansanga et al. 2019). In Asia, the link between tractor adoption and farmland expansion has been observed in both land-scarce and land-abundant settings (Pingali 2007). While farm expansion typically has environmental consequences that need to be weighed, since farming is seldom environmentally neutral, farm expansion does not automatically imply forest conversion or encroachment into natural ecosystems (Box). Annex 3 offers an expanded discussion on the environmental effects of mechanization and digitization.

Box 4: Does mechanization-enabled farm expansion benefit smallholder farmers at the expense of the environment?

Whether the expansion of cultivated area might have environmental consequences depends on the context. Mechanization-enabled farm expansion can be environmentally neutral if it results from a contraction in the number of farms and an increase in the average farm size. There is also a significant environmental difference between farms reclaiming and cultivating uncultivated or fallow lands, which can have either positive or negative effects on the environment; and the conversion of pristine ecosystems, which typically ravages biodiversity, carbon storage and ecosystem health. Mechanization has been associated with natural ecosystem conversion in some contexts. In Benin, Kenya, Nigeria and Mali, for example, surveyed farmers perceived tractor use to be largely beneficial, yet sometimes associated with soil erosion, deforestation and land-use conflicts (Daum et al. 2020). In Latin America, while mechanization has not been a driver of agriculture-related deforestation per se, it has in many cases been an enabler of it, considering that the cultivation of large expanses of converted savannah and forestland would not be possible without the use of large tractors (de Oliveira et al. 2017 in Daum 2023). In parts of Asia and Sub-Saharan Africa, where tree crops have been the major drivers of deforestation, mechanization of farming functions has generally played a minimal role. Most cultivation tasks in those systems have remained highly labor-intensive.

In many parts of the world, mechanization has enabled farmers to increase output by increasing cropping intensity and thus increase the overall planted area over the course of a year.[9] This phenomenon has notably been observed in Southeast Asia, where two to three rice crops can be grown on the same plot of land within a given year. Mechanized threshing is a key enabler of this scenario because it requires the capacity to rapidly thresh the paddy when it is harvested during the rainy season (first harvest), to avoid spoilage (Juarez and Pathnopas 1983, Pingali 2007). Tractors are also pivotal because they allow farmers to quickly prepare the land for a second crop, as are irrigation pumps. The mechanization of harvesting and planting functions also facilitates better-timed rotations between seasons and among different field crops (such as cereals and oilseeds), supporting more diversified farming systems.

Mechanization can also increase farm output and value by increasing crop yields in direct and especially indirect ways. Tractors directly enhance crop yields by improving tillage, weed control and water management (Mano et al. 2020); and indirectly, by encouraging higher-yielding practices. In many parts of the world, the adoption of tractors, irrigation pumps and power threshers have enabled the subsequent adoption of yield-increasing technologies, such as improved seeds, fertilizer and pesticides.[10] Direct seeding (rather than broadcasting of seeds) is commonly done in the more mechanized rice systems

[9] Diao et al. 2020; Pingali 2007; Pinstrup-Andersen and Hazell 1985; Singh 2001; Tetlay et al. 1990; Verma 2006 in Daum 2023
[10] Bhattarai et al. 2020; Diao et al. 2020; Ma et al. 2018; Mano et al. 2020; Nin-Pratt and McBride 2014; Takeshima and Lawal 2020 in Daum 2023

of Asia. Similarly, in Cote d'Ivoire, farmers who use two-wheel tractors for land preparation were found to be more likely to adopt better all-around practices for rice cultivation, thereby raising yields and output (Mano et al. 2020). In Tanzania, the adoption of two-wheel tractors increased paddy yields by encouraging farmers to plant modern rice varieties and transplant in rows (compared to farms using draft animals) (Magezi et al. 2020). Studies on early mechanization in South Asia also showed that higher yields on more mechanized farms were in large part explained by more effective fertilizer use (Binswanger 1978, Pingali 2007).

Mechanization can also increase sellable output by reducing the losses that occur during and just after harvest. One study in Kenya attributed 95% of potato damage and losses to a lack of harvesting technology (Breuer et al. 2015). Another study in India found that by reducing damage and losses, combine harvesters in rice farming (for harvesting and threshing) raised yields by 24% (Bhattarai et al. 2020 in Daum 2023). Mechanical harvesting, threshing and drying have been found to facilitate a decrease in breakage and contamination (Daum and Kirui 2021, Elverdin et al. 2018, Salvatierra-Rojas et al. 2017 in Daum 2023, Chege et al. 2023, Diao et al. 2020). Mechanical drying of maize, followed by proper storage, have been found to be an effective strategy for minimizing the incidence of aflatoxin contamination, a serious health hazard where maize is a food staple or major component of animal feed.

Meanwhile, the productivity-boosting effect of mechanization is only one aspect of its income-boosting effect. Time-freeing technology has been particularly game-changing for very small farms across Asia. Very small farms producing staple food crops are generally unable to generate a living income from their land, no matter how efficient they use that land or how well-connected they are to markets. Even generous area-based subsidies may fall short of lifting these farms out of poverty or near-poverty (although very high levels of subsidization in Japan and the Republic of Korea have helped keep some small farms in operation). For small farming households that remain staple food producers, income diversification may be the only pathway to a living income.

In Asia, mechanization-enabled income diversification has been key to breaking the income ceiling associated with very small land holdings at scale. Where mechanization has advanced in rice (and other production) systems, large numbers of farmers (or, more accurately, adult members of farming households) have been released to engage in other activities, including wage or salary employment, seasonal construction work, small business or more permanent migration (to cities), often remitting money back to the household. This is how things have played out in the main cereal producing areas of China, where farming functions are increasingly being performed by agricultural service companies, while the bulk of family labor time is devoted to nonfarm work and other more remunerative activities (Zhang et al. 2020; Deng et al. 2020; Lu et al. 2022). In Vietnam's Mekong Delta, while the mechanization of rice and other production systems has contributed to increasing farming income, its larger contribution to farmer incomes has come from freeing up farm household members to work off the farm in higher paying activities. Hence, while farming income in the region nearly doubled from 2010-2021, nonfarm salary and wage income increased eightfold and business-related income increased fourfold (Vietnam GSO 2022). Mechanization was an important enabler in this dynamic.[11] This pattern was also experienced in parts of Africa. In Benin, Kenya, Nigeria and Mali, a reduction of labor burden and the freeing of time for nonfarm activities were perceived by rural residents as the top positive effects associated with mechanization (Daum et al. 2020).

[11] Historically, mechanization has played an important role in driving the consolidation and professionalization of farming activities and releasing labor to other sectors of the economy. This phenomenon has generally benefitted farmers in contexts where mechanization has not gotten ahead of market forces and exiting farmers have been able to find nonfarm employment. In fact, public efforts to directly promote mechanization have a poor track record as they have often led to market distortions (Daum and Birner 2017; Pingali 2007 in Daum 2023). Conversely, fluid labor markets are considered essential for the rural poor to benefit from growing nonfarm opportunities (Haggblade et al. 2010).

As noted above, the evidence base linking digitization and farm productivity (and incomes) is less robust. The expectation is that farmers will benefit via improved access to relevant and trusted information, knowledge and farming advice. Digitization has the potential to multiply the number of farmers reached by resource-constrained extension services by slashing the cost of reaching each additional farmer. Digitization also has the potential to increase the quality and relevance of extension by connecting farmers to a wider and deeper pool of expertise and knowledge, enabling them to solicit that knowledge or expertise when they need it, and more generally allowing for the mass customization of extension content. Digitization is also seen as offering new means of facilitating the uptake of knowledge by overcoming communication and trust barriers, including by enabling machine translation and peer-to-peer knowledge exchange (notably via social media and certain extension platforms).

While available evidence is in some cases very positive, the promise of digitization to improve yields via the delivery of tailored information and knowledge may largely lie ahead. One already cited review of evidence from Africa found various agricultural applications of digital technology to have significant yield improvements, hovering around 20% for advisory services, 40% for financial services and 70% for market linkages (Tsan et al. 2019). However, while the provision of information and knowledge has been a leading application of digital technology in LMIC agriculture – as well as one of its most studied applications – its development and adoption is considered to be in early stages (CTA 2019, Birner et al. 2021 in Abate et al. 2023). In Rwanda and Kenya, studies have shown SMS-based agricultural extension programs to have had positive yet moderate effects on farming practices (the adoption of inputs) (Fabregas et al. 2019). Evaluations of Digital Green's video-based, peer-to-peer extension platform in India and Ethiopia showed significant yet relatively weak and short-lasting effects of video-based extension on knowledge, the adoption of practices, yields and output, among other outcomes (compared to traditional extension) (IDinsight 2021). Nonetheless, the Indian government's recent commitment to mainstreaming Digital Green in its national extension system is a strong endorsement of the system.(MOA&FW 2023).

Another key way digitization is expected to benefit farmer incomes is by enhancing their access to markets and bargaining power, as well as by disintermediating markets and increasing market efficiency. It is generally expected to do this by allowing farmers to discover the market price of items they wish to buy or sell, learn about what the market wants, document their transactions, connect more easily to buyers and sellers and spend less time and money getting to market or arranging transactions.[12] And indeed, there is some empirical evidence that tools like mobile-based market information systems, mobile payments and e-commerce platforms have, in some cases, allowed farmers to participate in markets, cut out market intermediaries, secure competitive and agreed upon prices and avoid being taken advantage of (World Bank 2012, Sekabira and Qaim 2017, Grossman and Tarazi 2014, World Bank 2016, Fabregas et al. 2019, Aker and Cariolle 2020, Banerjee et al. 2020, in Abate et al. 2023). There are many examples of this cited in the literature for Africa.[13]

Meanwhile, the widescale use of the most successful agrifood e-commerce platforms suggests that they are serving the millions of farmers who have turned to them.

[12] In more economic terms, digitization is expected to increase market transparency and reduce information asymmetry and transaction costs.

[13] For example, ICT-based market information systems have been shown to strengthen farmers' links to markets, reduce transaction costs and increase agricultural incomes in Malawi (Ketengeza et al. 2013 in Abate et al. 2023). In Northern Ghana, one model showed that mobile-based MIS (Esoko) could increase farmers' bargaining power, resulting in them receiving 10% higher prices for maize and 7 % higher prices for groundnut (Courtois and Subervie 2015). In Uganda, one study found that radio-based market information systems increased farmgate prices (Svensson and Yanagizawa 2009 in Abate et al. 2023). In Ethiopia, one study showed that access to price information facilitated by the (publicly run) agricultural commodity exchange (ECX) influenced farmers' crop choices and increased the average farmgate prices for traded commodities (Belay and Ayalew 2020). One study in Niger found that access to mobile phone service reduced price variation (Aker 2010) across markets and over time for semi-perishable commodities (Aker and Fafchamps 2015 in Abate et al. 2023).

Privately developed and run platforms, such as Pinduoduo and Alibaba in China, seem to be giving farmers access to distant urban markets they previously had no means of reaching, including by training them to meet market expectations in terms of safety, freshness and presentation. In India, BigHaat and AgroStar seem to be facilitating farmer access to inputs on a large scale. In Kenya, Twiga Foods has reportedly worked with 40,000 small retailers across the country (although only about 4,000 farmers), representing approximately 25% of the food distribution industry (Chege and Onyango 2023).

Moreover, a number of factors may help smallholders leverage digital technology to develop market linkages and power. For example, smallholders may be better positioned to leverage digital technologies when public oversight and farmer (co-)ownership or (co-)management of technology ensures that they increase market transparency and competition. Farmers may also be in a better position to take advantage of digital technology when they are already strongly organized or able to use digital technologies to strengthen collective action.

That said, some empirical studies point to digital tools having a more neutral effect. For example, a study in Malawi found that mobile-based market information systems had no effect on farmers' participation in markets (Chikuni and Kilima 2019 in Abate et al. 2023). Another study in Ethiopia found that mobile phone ownership had little effect on farmer prices, although it increased the amount of marketed surplus (Tadesse and Bahiigwa 2015 in Abate et al. 2023). In Rwanda, one study found that Grameen/MTN village phone had no effect on prices or profit (Futch and McIntosh 2009 in Abate et al. 2023). In this context, the relative lack of empirical evidence may not be neutral, but rather a reflection of the challenges associated with developing systems that farmers value enough to continue using once they are no longer subsidized by donor projects.

Both mechanization and digitization may help farmer incomes by helping them mitigate or better manage risk, including but not limited to weather and climate risk. By allowing farmers to work faster, mechanization can sometimes enable them to respond more flexibly to changing weather patterns (Elverdin et al. 2018 in Daum et al. 2023). To the extent that mechanized pumping can facilitate irrigation, it is also implicated in the adoption of a technology that can help stabilize yields and incomes in the face of weather risk (notably drought) (Malabo Montpellier Panel 2018; Pingali 2007 in Daum 2023). By providing farmers accurate and timely weather forecasts and advice, digital information services are expected to better equip them to navigate the rising levels of uncertainty brought on by climate change; by for example, determining whether and when to plant crops, when and how to act against pest outbreaks or how to optimize the use of dwindling water stores.

The capacity of a given technology to benefit farmer incomes critically depends on the income constraints they face and how well-suited the technology is to addressing them. For example, labor-saving technology such as mechanization can help boost the (farm or nonfarm) incomes of farmers when these are constrained by the limited availability and high cost of farm labor.[14] In China, for example, mechanization – and more specifically, mechanization services – have enabled large numbers of small farms to cope with labor shortages and rising rural wages linked with urbanization, the development of the nonfarm economy and farmer aging.[15] But where such time and labor constraints are not present, the same technology could or would detract from farmer incomes by raising their production

[14] From an equity perspective, as discussed below, this boost can be particularly felt by female farmers whose incomes can be particularly constrained by a lack of time to engage in more lucrative work, considering much of their time is taken up by low-paying or unpaid work. Mechanization may enable them to take on more lucrative farming or off-farm activities (such as horticulture or processing), provided market opportunities are available and other enablers like access to finance and other means of production are in place.

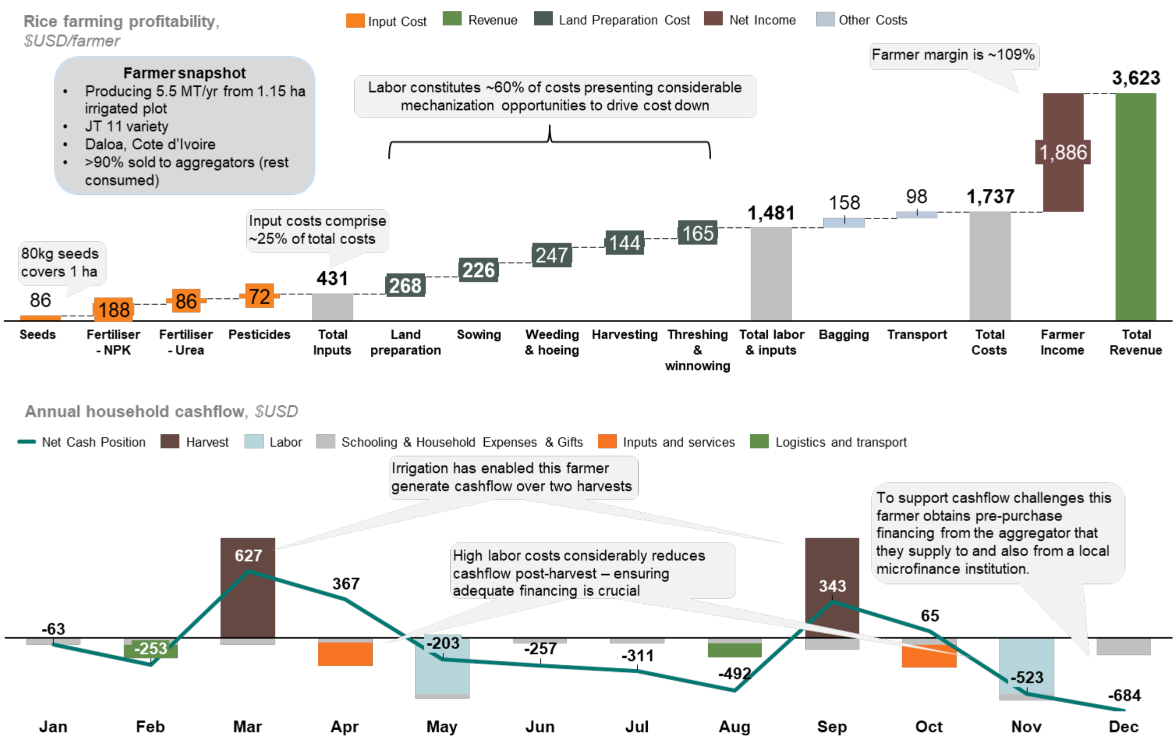
[15] While the overall number of people (primarily) employed in agriculture has been plummeting, the quantity of machine power employed in the sector has risen steadily. There has also been a significant shift in the division of labor between small farm landowners, hired part-time workers and mechanization service company employees.

costs without a commensurate increase in revenues (and for hired farm workers, potentially causing unemployment, as discussed below).

However, this scenario is not overly concerning from a farmer welfare point of view, as, farmers are unlikely to adopt the technology in the first place in these cases. One comprehensive study of agricultural mechanization in Asia stresses that mechanical threshing is only economically efficient when farmers (1) face a power bottleneck during the harvesting-threshing period due to low availability or high costs of labor and (2) have the means to earn more by producing more (Pingali 2007). The latter implies that there is unmet demand for what the farmer produces and that supplying more of it will not overly depress prices such that incurring the additional costs of producing more is worthwhile.[16] That said, it is empirically noteworthy that in intensively cultivated systems in Asia, farm mechanization (of power-intensive operations) has been profitable, even under low-wage conditions (Pingali 2007). These historical cases indicate that farm economics, especially labor costs and returns on investment, must be well-understood prior to investing in the scaling of mechanization services. In one analysis of rice farms in Cote d'Ivoire, labor costs constituted 60% of farmer production costs, making mechanization a viable alternative (Figure 6).

Figure 6: Analysis of Costs on Rice Farms in Cote d'Ivoire, 2020

While irrigation offers an opportunity for a 1-hectare rice farmer to generate four times more profit, negative cash flows and insufficient profitability require supplemental, diversified income.



Source: Rogers MacJohn LLC (2020) field research and analysis on behalf of the Bill & Melinda Gates Foundation.

[16] In simpler yet more technical terms, condition (b) is that there be elastic demand for the farmer's output.

In the absence of empirical evidence, parallel reasoning can be applied to the digital world. When farmer incomes are constrained by a lack of access to markets or by their dependence on market intermediaries who eat into their profits, digital technologies may help elevate them by linking farmers to markets and disintermediating them, while also increasing market transparency. But if farmers do not face such constraints, then it would not make economic sense for them or any other party to pay for services designed to overcome them.

Technology adoption is often associated with a simultaneous increase in risks and returns, and mechanization and digitization may follow this pattern. Mechanization and digitization can introduce qualitatively new or higher levels of risk for farmers, sometimes in unforeseen ways. In general, technologies may be more likely to create new vulnerabilities when: (1) technology dependence is high, giving farmers fewer alternatives when a problem arises; (2) in contexts where relevant services, infrastructure and consumer protections are weak; and (3) when technology costs loom large in relation to farmers' net worth.

Both mechanization and digitization can cause farmers to depend on technology, at least within the timeframe of a growing season. This can render them newly vulnerable to fuel or electricity price surges (Daum and Birner 2017; Elverdin et al. 2018), breakdowns, platform malfunctions or service delays. Machines can break down or service providers may arrive late or not at all, which can heavily affect timely production and yields (Daum and Birner 2017). Although motor pumps offer significant income-generating opportunities (on farm and off-farm by freeing up time), maintenance, access to spare parts and water shortages can be major challenges (Glatzel et al. 2018).

Mechanization can also sometimes introduce longer term risks, like when its use (or perhaps its misuse) contributes to soil degradation or a resurgence of pests, or greater farm specialization (a source of vulnerability) (Antle and Ray 2020; Kansanga et al. 2019). Technology adoption risks may be exacerbated by weaknesses in public and private services and infrastructure, including training, roads and the availability of machines, parts and servicing.[17] For example, poor transportation infrastructure increases the cost of accessing machinery, spare parts, repairs and fuel, and impedes the emergence of (migratory) service markets (Daum and Birner 2017; Mrema et al. 2008 in Daum 2023). Risk factors also include farm specialization (which can decrease farm resilience) and dependence on supplied inputs or technologies, such as specific types of seeds and farming chemicals.

Farmers generally have to borrow money and pay to use machinery, and this alone can put them at substantial risk, given the technology may not serve them as expected. In Benin, Kenya, Nigeria and Mali, higher production costs associated with mechanized farming increased overall financial risk levels reported by farmers (Daum et al. 2020). In India, the fact that farm machinery is expensive has raised concerns over whether it is financially viable and sustainable to own and use on smallholder farms (Gulati and Juneja 2020). The development of rental and mechanized service markets may be critical in these contexts. In contrast, farmers generally have little to lose from adopting digital technologies, even if they end up not being particularly beneficial, given they often pay little to nothing to use them. However, digital platforms potentially have hidden costs for farmers if they give rise to an erosion of market competition (through a situation of concentrated market power), leading to higher input or lower output prices over time.

[17] Restrictions on who can fix machines – as sometimes seen in high-income countries – could make this situation even worse.

2.2 Occupational Health and Safety and Attractiveness of Farm Work

How and to what extent have mechanization and digitization helped enhance occupational health and safety, attractiveness and protection of farm work? When and how have these technologies had unintended consequences?

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.	• The use of machinery exposes farmers 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 risks to keep their jobs or maintain their wages.

Mechanization and digitization – or specifically automation – can decrease certain occupational health and safety risks associated with farm work. Mechanization generally reduces reliance on human power to perform routine farming tasks and there is abundant evidence that mechanization can lessen the strenuousness of agricultural work. In some respects, it can also lessen its danger. In the absence of mechanization, farming is typically associated with backbreaking work, which can undermine wellbeing and health (Sims and Kienzle 2006). This drudgery is particularly high in tropical conditions and will likely be intensified by climate change (Dasgupta et al. 2021). In many parts of Asia, including Vietnam, transplanting machines have greatly reduced labor demands, drudgery and health risks for rice farmers (Nguyen-Van-Hung et al. 2023). And mechanization can reduce worker exposure to hazards in post-harvest tasks, such as in the shelling of cashew nuts. Automation, while largely prospective in the context of LMIC agriculture, promises to further improve the safety of farm work. Automation could improve safety, in part, by curtailing opportunities for human error and reducing the need for manual labor in the first place.

However, farmers' contact with machines and farm equipment, and the robotic enhancement of farm labor, can also introduce new hazards, exposing workers to the risk of traumatic and repeated use injuries. Technology can also indirectly lead to injury by increasing farmers' exposure to hazardous agrochemicals or driving workers to speed up their work (the latter could result from digital monitoring of farm work). The risk may be higher in unregulated and unmonitored spaces where workers are poorly trained or the equipment is not well-maintained or functioning properly. Without adequate and proactive protections in place (state-provided or user-based), some farmers or workers may be at greater risk of harm from the use of technology, including from the intended and unintended uses thereof. Some users may lack the means or motivation to protect themselves, and certain technologies may increase the severity of farming hazards.[18]

In the course of mechanization and automation, risk levels may increase before they decrease, as technology designs and safety protocols evolve to help mitigate the new risks they introduce. Operator safety and comfort is a growing concern when humans interact with machines. In India, the accident rate per 1,000 workers is significantly higher in the less-mechanized Southern India than in Northern India, but it also appears that the

18 One study in Ghana observed that none of the tractors it sampled were built with rollover protection structures; and that only a minority of surveyed operators took simple protective measures like wearing heavy-duty boots (50%) or close-fitting clothing (5%) (Aikins and Barkah 2012 in Daum 2023). Still in Ghana, another study found that 36 percent of surveyed operators had no valid license to operate any car, truck, or tractor (Aikins 2012 in Daum 2023).

surplus of accidents in Southern India is related to agricultural machinery, and in many cases, its “misuse” (Yadav and Mohan 2019).

Mechanization, and more prospectively, automation, have the potential to make farm work more attractive by creating the conditions for more psychologically fulfilling work. This typically applies to work that offers more opportunities for autonomy, mastery and purpose (Pink 2009), and it is conceivable (though unproven) that mechanization and digitization could create such opportunities. In certain LMIC contexts, some argue that mechanization may also be associated with psychological fulfillment because of its association with a higher social status (Daum, Capezzone, and Birner 2021 in Daum 2023). That said, mechanization may negatively affect farmers’ mental health if they struggle to repay debts taken to finance machinery or mechanization services (Daum 2023).

If automation and mechanization have the potential to make work less fulfilling and less well-remunerated, this risk seems less pronounced in the context of farming than in the context of agro-processing, and may even have the opposite effect. Some have expressed concerns about the potential for digital tools to enable a deskilling of farm work, in parallel with increased worker surveillance (Prause et al. 2021, Hackfort et al. 2020). While these tendencies have been witnessed in other sectors (a phenomenon perhaps epitomized by mass product fulfillment warehouses), and some farm automation has occurred in LMICs on an experimental basis (like Vietnam), so far there is little empirical evidence to bear out these fears in the context of farming. In fact, farm mechanization and automation may contribute to enhancing the attractiveness of farm work among youth and more educated workers. There is some evidence of this from programs run in Japan and South Korea seeking to attract youth to form the next generation of farmers.

2.3 Hired Farm Worker Employment, Wages and Working Conditions/Protections

How and to what extent have mechanization and digitization supported the employment, wages, working conditions and protections of hired farm workers? When and how have these technologies had unintended consequences?

KEY OPPORTUNITIES	KEY RISKS
• As technology increases, the skill requirements of farm work, and therefore, the remuneration and stability of hired farm work increases. • Organizations and companies monitoring forced labor and exploitative labor situations in supply chains can 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). • Farm workers are better equipped to avoid and report forced labor and exploitative work situations. They are informed about their rights, have records of what they agreed to and have access to data about their work and output, as well as grievance mechanisms • Child labor decreases as a result of increased productivity.	• Farm workers see their earnings decline due to underemployment and/or a decline in 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. • 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, increase production and ultimately extract more from them.

The effects of technology adoption on demand for hired farm workers and their wages is highly context dependent, but it is not a foregone conclusion that technology will displace hired farm workers and leave them worse off. Amid rising labor productivity, mechanization can lead demand for agricultural labor to decline, stagnate or increase, depending on the context (Daum 2023).

Technology adoption can depress the employment and wages of hired farm workers in certain contexts. Both agricultural mechanization and digitization have the potential to reduce the demand for low-skilled labor, lowering their wages and leading to more underemployment in rural areas. Mechanization, for instance, has the potential to reduce the need for manual labor to carry out (labor-intensive) planting, weeding and harvesting activities, reducing reliance on temporary workers and changing seasonal employment patterns in agriculture. The availability of seasonal work opportunities may also become more uncertain.

Empirically, concerns that mechanization leads to unemployment have been substantiated in contexts where there is a surplus of labor (Binswanger and Donovan 1987; Daum and Birner 2020; Pingali 2007 in Daum 2023). Such conditions typically exist when farmers face few opportunities for nonfarm employment. In the Philippines, surveys from the 1980s found that post-harvest labor on mechanized farms in Nueva Ecija, the country's rice basket, was 25% lower than on farms where rice was manually threshed, and that much of the labor savings came at the expense of landless households, whose labor demand declined by 31% (Duff 1986 in Pingali 2007). This and other early developments may have contributed to the more limited support for rice system mechanization offered by the Philippine government compared to the pattern observed in other Southeast Asian countries.

However, lower demand for hired workers (due to mechanization) does not automatically result in would-be farm labor becoming worse off. In Asia, higher levels of mechanization are not only associated with less reliance on labor to farm each hectare of rice, but also with less relative reliance on hired workers (Mataia et al. 2016). In other words, hired workers carry out a smaller proportion of rice farming work in more mechanized countries. But in countries like China, where rural workers have faced relatively attractive off-farm employment opportunities, farm wages have actually increased in tandem with mechanization (Mataia et al. 2016). The same pattern was observed in Myanmar as mechanization accelerated in the mid-2010s (Benton et al. 2021). In these and other cases (like Vietnam), the "pull" of off-farm work opportunities has been much stronger than any "push" or labor-sparing effect of mechanization. In these more dynamic economies (rural and overall), declining labor availability and increasing labor costs have tended to induce further mechanization.

Moreover, mechanization does not always reduce the total demand for labor. Mechanization and digitization can both generate more farm work by enabling its extensification or intensification, thereby stimulating demand for hired farm workers and their wages. In Zambia, one already cited study showed that, while mechanization reduced the number of workers needed to farm each hectare, overall labor needs were maintained, since mechanization allowed farms to expand (Adu-Bafour et al. 2019). One study in Cote d'Ivoire found that the mechanization of rice farming increased labor needs per hectare, even though mechanization increased labor productivity (Mano et al. 2020). In that example, farms using tractors for land preparation were also more likely to adopt labor-intensive practices associated with higher yields.

Critically, mechanization does not typically increase unemployment where it emerges as a response to market forces. These market forces might include rising rural wages, due to structural transformation, and the need to replace unpaid family labor (Binswanger 1986, Daum and Birner 2020 in Daum 2023).

At times, mechanization may stimulate employment opportunities beyond the farm. Mechanization may have this effect by increasing overall production volumes and generating local processing or other upstream or downstream opportunities. Mechanization may also create jobs relating to the sale, maintenance or operation of farm machinery; that is, in agricultural service industries. In another scenario, mechanization may stimulate rural employment by enabling farming households to prosper, causing positive spillover effects in the rural economy at large.

While mechanization and digitization both have the potential to either negatively or positively affect agricultural wages and the nature of farm work by affecting its skill requirements, empirical evidence is generally positive. There is a lack of empirical evidence supporting the scenario in which technology leads to a deskilling of labor, lower wages and less fulfilling work, at least at the farm level. However, concerns are borne out in the context of industrialized agrifood processing, based on evidence from high-income countries. Conversely, there is some evidence from high-income countries that mechanization and automation can generate jobs with higher skill requirements, leading to higher-paying and more stable jobs for those who can learn new skills (Prause 2021). In theory, as agricultural machinery and technology become more sophisticated, there could be a need for continuous training and upskilling of rural labor, leading to increased job security. Technology-enabled increases in farm profitability – linked to improvements in productivity, quality or market access and bargaining power – could also translate to higher wages for those who remain employed by farms. Separately, digital platforms could conceivably facilitate the search for seasonal workers and jobs, resulting in more efficient labor markets and, in turn, less unemployment and a competitive leveling of wages. Digital platforms could also potentially help seasonal workers secure market wages more efficiently and ensure they are fairly remunerated.

In circumstances where mechanization reduces the demand for manual, unskilled labor, it could potentially lower the incidence of forced and child labor. However, the evidence for this is not entirely conclusive. There is evidence that the use of tractors or combine harvesters on farms generally reduces children's employment in intensive agricultural labor (FAO-IFPRI 2022). This was shown to be the case in several African countries, though not in Tanzania. In Ghana, child labor declined by up to 30%, with variations depending on whether machine power was used for land preparation, planting or harvesting (reductions in child labor may be more pronounced during planting). In India, the use of tractor and combine harvesters reduced the probability of children's farm and nonfarm work by an average of 5-10%. However, a review of household survey data across seven countries did not yield a clear conclusion. Some examples were found where mechanization led to a shifting of chores from hired labor to children (for example, for weeding edges of farmland not accessible by machinery). The type of production system (like crop versus livestock) and levels of school attendance may be important factors influencing outcomes.

While there is hope that digital technologies will help root out child labor, these remain incipient and unproven. For example, efforts are reportedly being made to leverage GIS and blockchain technologies to facilitate real-time, cost-effective and collaborative monitoring of child labor in the cocoa-growing areas of Ghana (Termeer et al. 2023). These systems require further development of digital infrastructure in rural areas and would rely on methods ensuring data quality and relevance. Currently, the monitoring of child labor within the cocoa industry is carried out through monitoring visits and household surveys.

As their use develops, digital technologies may have the potential to enable the surveillance and overdriving of workers, especially when farmers lack capital, legal protections or recourse. In contexts where farm workers are employed in relatively large numbers, as in plantation agriculture, digital technologies could conceivably enable more ubiquitous worker monitoring or surveillance and control, resulting in a loss of civil liberties and "exploitation" in the presence of unmitigated information and power asymmetries, and an under-recognition and insufficient protection of farm workers' rights. These risks may be especially pronounced where farm workers have weak human, social and economic capital; for instance, among those who are less educated, literate, digitally savvy, organized and resourced, and where regulatory or user-based safeguards and protections are not in place.

Unskilled migrant workers face particular vulnerabilities in this respect. The risks they face include exploitation, forced labor, deception, debt bondage and financial and identity theft. According to migrant protection NGO Seefar, there are concerns that digital platforms could increase the vulnerabilities of migrant workers in general, particularly in the absence of robust privacy and data protection laws. These concerns are most pertinent to large-scale plantation agriculture where the use of migrant labor, including international migrants, is quite common. These issues are far less pertinent to workers hired for small-scale agriculture, where most workers are local or part of a seasonal movements of workers, repeated annually.

Digital technologies could be leveraged to counter such risks and facilitate improvements in the working and employment conditions of hired farm workers. In general, their promise lies in their potential to enhance market transparency, farmers' knowledge, options, voice and influence, and sector stakeholders' risk assessment capacity. That said, for all of its promise, it is unlikely that digital technology on its own will dismantle the (social and economic) systems and circumstances that perpetuate the exploitation of migrants and other workers.

Part of the promise of digital technologies lies in their potential to better inform farm workers and equip them to stand up for themselves. Digital tools are opening new channels for farm workers to learn about going wages, alternative job opportunities, occupational health and safety standards and worker rights, as well as connecting them with peers and support structures. In these ways, digital tools could empower farm workers to seek out or bargain for better working conditions, treatment and fair pay.

Digital tools may also empower farmers to recognize and report poor working and employment conditions in contexts where grievance or monitoring mechanisms are known, trusted and in place. The hope is that by making it anonymous, fast and cheap for farmers and other stakeholders to report problems, digital tools like SMS will help overcome time, mobility, safety, cost and other reporting constraints. There is some evidence that migrant workers are engaging with platforms to access migration information and at times register complaints about illegal recruitment practices. For now, it is unclear whether reporting has led to an increase in the number of labor inspections or a reduction in unethical recruitment practices (Seefar 2022).[19]

For grievance mechanisms and abuse reporting to be effective, actors on the receiving end of complaints must be equipped and prepared to respond, and technology is no substitute for that capacity. Moreover, technology is unlikely to help worker trust in existing grievance mechanisms (ILO 2021). In many cases, the labor-hiring process smallholder farms engage in is informal and may be beyond the scope of regulatory enforcement. Yet, some supply chains are under intensifying pressure to root out bad labor practices. In this context, the development of the digital recruitment of agricultural labor is enabling new means of detecting and preventing abusive and forced labor situations.

One promising (though largely unproven) application of digital technology lies in steering migrant recruitment to reputable online recruitment platforms. In theory, at

[19] Some digital tools are being used to detect labor violations in ways that rely less on workers reporting problems. Recognizing the challenges of attracting the most at-risk individuals to centralized recruitment sites, and relying on whistleblowers, one NGO has developed a tool that aims to detect labor violations using information people are already sharing online. Through an initiative known as Social@risk (not specific to agriculture), the Swedish non-profit Globalworks has attempted to use machine learning to monitor millions of social media posts, job postings and other websites for red flags relating to labor rights violations (Ro 2022). In this case, the intent is to capture unfiltered, unprompted information that people are already sharing online (Ro 2022). This example highlights another promising application of digital technology in combatting worker rights abuses.

least, recruitment platforms create opportunities to inform, educate and alert job seekers; standardize, document and increase transparency in the recruitment process (reducing opportunities for deviance); and monitor recruiters. Moreover, with platforms like Recruitment Advisors, workers interested in using recruitment platforms can consult public ratings of them online.

However, little research has measured whether the digitization of migrant labor recruitment has affected rates of exploitation and forced labor, in either positive or negative ways. There is limited published data on whether digital recruitment platforms facilitating access to personal documents have contributed to reducing exploitative situations, such as wage theft and the confiscation of IDs (Seefar 2022). Moreover, governments frequently lack effective labor inspection systems and have limited resources to monitor migrant recruitment websites for unlicensed recruiters or to act on known violations (Seefar 2022). Furthermore, some of the most vulnerable recruits may not find their way onto these sites due to awareness, trust and literacy limitations.

Increasingly, watchdogs and corporate actors are turning to advanced analytics and AI to identify risks and where to carry out more in-depth supply chain investigations. There is hope that these digital technologies will generate new and better insights by using available data and computing power. By the same token, there is also hope that they will allow supply chain stakeholders to make more efficient use of the scarce resources they have to monitor what are often vast and complex production systems. In this case, digital tools are being used to guide a more selective and risk-based deployment of resources, allowing stakeholders to carry out more in-depth investigations in areas identified as high-risk hotspots. Another potential advantage of digitally enhanced supply chain monitoring is that it can be carried out more continuously, offering a better idea of supply chain realities than a snapshot from a single point in time can. That said, technology is unlikely to overcome all the shortcomings of traditional social auditing.

Various digital tools have been developed to track and analyze labor issues in agricultural and other supply chains. For example, Verite.org has deployed tools to scrutinize labor rights violations, including child labor, forced labor and gender discrimination in the cocoa, palm oil, coffee, sugarcane and seafood value chains. Ulula, a company leveraging technology to monitor and defend human and worker rights in supply chains, has developed a suite of digital tools to monitor agricultural and other supply chain, notably in preparation for the EU's forthcoming Corporate Sustainability Due Diligence Directive (CSDDD) (Box 5).[20] The company notes that it is using deliberately low-tech solutions (like basic mobiles to communicate with workers and others involved in supply chains) to monitor child labor, educate workers about safety and worker rights, provide them with access to grievance mechanisms and carry out anonymous surveys to reveal labor risks in sourcing regions. Sedex, a supply chain auditing company, is leveraging advanced analytics to detect risk in supply chains and increase the efficiency of social auditing. ELEVATE, another supply chain auditing company, has started using a mobile-based digital platform, Laborlinks, to

[20] https://ulula.com/sectors/agriculture/.

monitor working conditions in agricultural and other supply chains, including by enabling worker surveys and grievance reporting.[21]

Box 5: Toward a new era of corporate responsibility: the EU's forthcoming CSDDD

If adopted, the Corporate Sustainability Due Diligence Directive (CSDDD) will require companies operating in the EU to establish due diligence procedures to address adverse impacts of their global actions on human rights and the environment. The CSDDD was introduced by the European Commission, pursuant to the European Green Deal.

While some (smaller) companies will be exempt, those within the scope of the directive will likely have to implement due diligence measures to identify, end, prevent, mitigate and account for the negative human rights and environmental impacts of their actions. The latter will, among other things, involve developing and implementing "prevention action plans," obtaining contractual assurances from direct business partners and subsequently verifying compliance. Companies covered by the directive will be responsible for applying due diligence not only to their own internal operations, but also to the entities within their supply chains with which they have a direct business relationship. Larger companies will also be required to develop a climate mitigation plan in alignment with the Paris Agreement on climate change.

The directive covers a wide range of labor, human rights and environmental violations, including the right to dispose of a land's natural resources and to not be deprived of means of subsistence; the right to enjoy just and favorable work conditions, including a fair wage, a decent living, safe and healthy working conditions and reasonable limitation of working hours; the prohibition of child labor; the prohibition of unequal treatment in employment; the right to liberty and security; and the prohibition of causing any measurable environmental degradation, such as harmful soil change, water or air pollution, harmful emissions, excessive water consumption or other adverse impacts on natural resources that affect ecological integrity, such as deforestation or activities with a range of other ramifications

[21] A number of potentially relevant tools have been developed in the context of other sectors, including the garment, construction and electronics industries**.** For example, with support from the UK government, the Global Fund to End Modern Slavery has developed a predictive modelling tool known as the Forced Labor Automated Risk Estimator (FLARE), which the organization claims is 80% accurate following a pilot in the Indian garment sector (Ro 2022). The tool uses open-source or third-party data such as location, trade records, business intelligence data and company registry data to identify risk in firms at scale, processing data from tens or hundreds of thousands of firms. Where sufficient data is available, the tool generates risk scores for firms in the supply chain, enabling buyers to identify high-risk suppliers and carry out more in-depth investigations focused on potentially problematic procurement arrangements (ELEVATE website 2023, https://www.elevatelimited.com/blog/disrupting-forced-labor/). SA international has developed a tool meant to identify questionable labor practices in the apparel industry by enabling buyers to assess supplier capacity (using the Supplier Capacity Platform) and compare it to what they actually deliver (SA International, https://sa-intl.org/programs/faircapacity/). Some organizations are looking to blockchain technology to document contracts. The claim is that indelible contractual records could help employers pay lower wages or otherwise deviate from agreed upon terms (Zimiles et al. 2020).

2.4 Differentiated Effects on Women and Groups of Farmers (On Both Incomes and Working Conditions)

What are the equity implications of technology adoption? When and how have mechanization and digitization left certain groups of farmers at an even greater disadvantage? When and how have female, smaller or marginalized farmers particularly benefitted from these technologies?

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 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. This could involve female, less literate or more asset-poor farmers with fewer prerogatives, limited access to finance, less land, less education and so forth. • Technology leads certain farmers, notably women, to have to take on more unpaid or low-paid work and/or lose control over household resources. • Farmers are displaced from their farmland (due to the expansion and encroachment of other farms).

Both mechanization and digitization have the potential to be particularly helpful in terms of improving the economic prospects and working conditions of more marginalized and asset-poor farmers. Among smallholders, female, landless, more remote, less educated and otherwise less well-endowed farmers often face particular income constraints and work-related challenges. In theory, technology has the potential to be particularly valuable to these farmers, provided it is accessible and adapted to their needs. Both mechanization and digitization are expected to save farmers time and money accessing things like water, knowledge, productive inputs and markets, leaving them with more time to engage in income-generating activities, on or off-farm. Digital technologies are expected to give more farmers access to knowledge and skills, notably by stretching the scarce resources and outreach capacity of extension systems, and by skirting the need for farmers to travel to in-person training sites. Some technologies (like machine tools and automation) could conceivably level the playing field among farmers with more or less knowledge by reducing the need for it. While some types of equipment require expertise and training to be operated, others make the same work accessible to the unskilled and untrained.

Both types of technology also have the potential to directly address a range of productivity constraints and occupational health and safety challenges that loom large for many female farmers. Many women are particularly constrained by a lack of time and mobility (needed to access knowledge and input and output markets, and to work collectively with other farms), a lack of rights and collateral (needed to access finance) and at times, a lack of physical capability. They also often bear the brunt of highly strenuous farming tasks, like transplanting seedlings, weeding and pounding grain.

Various studies confirm that power equipment can help overcome the time and farming control limitations facing many women. In several LMICs, mechanized tillage has benefited women more than men by lowering weeding requirements, a job typically performed by women. In India, one study found it reduced female labor by 22% between 1999 and 2011 (Afridi et al. 2020) and similar patterns were observed in several African countries (Baudron et al. 2019a, b, Daum, Capezzone, and Birner 2021 in Daum 2023). Technologies like motorized irrigation have also been shown to reduce the time women and girls spend on tasks like fetching water (Malabo Montpellier Panel 2018). In Asia, mechanized milling has spared many women the laborious tasks of de-husking, pounding and milling grain (Pingali 2007). Moreover, it has been shown across LMICs that the reduction in women's workloads has enabled them to take on other agricultural activities (such as livestock keeping or gardening), off-farm work and leisure and care activities (Johnston et al. 2018; Theis et al. 2019). In Benin, Kenya, Nigeria, Mali and Tanzania, mechanization has also sometimes empowered women by reducing their dependence on male labor and allowing them to take on "male" crops and activities (Daum et al. 2020, Fischer et al. 2018).

That said, mechanization has been shown to lead, in some cases, to a higher workload for women. In the Philippines, before the adoption of mechanical threshers, men mainly carried out this manual task, which requires a large amount of physical strength. Once mechanized, women were left to take over threshing while men pursued more lucrative off-farm work (Ebron 1984 in Pingali 2007 in Daum 2023). The mechanization of "female" crops and activities has also been shown, at times, to weaken the decision-making power of women to the extent that their labor is no longer needed. Examples of this have been documented in India, Zambia, Tanzania and Ethiopia (Carranza 2014; Daum, Capezzone, and Birner 2021; Fischer et al. 2018; Van Eerdewijk and Danielsen 2015 in Daum 2023). Moreover, most attempts at mechanizing crop establishment and crop care activities in Asia have failed, in contrast to the mechanization of land preparation, transplanting, threshing and milling (Pingali 2007). Hence, whether or not power equipment helps to empower women depends on various factors in the local context.

Digital technologies are also expected to alleviate a range of challenges faced acutely by women, although empirical evidence supporting this is more limited. Digital extension and advisory services and farmer-to-farmer social media platforms can presumably help women overcome time and mobility barriers to collaborative initiatives and accessing knowledge, data-based advice and markets. Mobile banking and e-commerce may be sufficiently disruptive to open the doors to the participation of women. In Kenya, FarmDrive has helped smallholders, including women, gain access to financial services by using data to assess their risk profiles (Das and Landani 2020).

Notwithstanding potential adoption risks, barriers to adoption and full use are the key equity risk associated with mechanization and digitization, and targeted measures may be warranted to overcome them. In the former case, the key risk lies in the unintended consequences of technology *adoption*; in the latter case, it lies in *non-adoption* (or partial adoption). Technology is often less accessible to farmers with less wealth, access to finance, land, natural capital, knowledge, time, public infrastructure, technology, decision-making power, rights and social capital.

Across much of the world, mechanization still tends to be more common on larger farms (Berhane et al. 2020; Elverdin et al. 2018; Gulati and Juneja 2020; Takeshima 2017 in Daum 2023; Bhattarai et al. 2020). For example, tractor ownership in India has remained strongly concentrated among medium-large farms (>10ha), 38% of which owned tractors as of 2009 versus 18% of medium farms (2–10ha) and less than 1% of small farms (<2ha) (Bhattarai et al. 2020). Small-scale operations require less work and generate less income, making it harder to justify mechanization costs.

There is strong evidence that women often have less access to mechanization than men. This has been observed in various LMIC settings (Ahmed and Takeshima 2020; Daum and Birner 2017; Daum et al. 2020; Fischer et al. 2018; Kirui 2019; Njuki et al. 2014; Theis et al. 2019 in Daum 2023). One study found that female-headed households had far less access to motorized mechanization in 13 of 15 LMICs studied, and that access was particularly limited in households where women were the heads and no other male adults were present (Croppenstedt et al. 2013 in Daum 2023).[22] Reasons for lesser (or delayed) adoption include social norms, socioeconomic disadvantages like less access to credit and more scattered plots (Ahmed and Takeshima 2020; Badstue et al. 2020; Croppenstedt et al. 2013; Daum and Birner 2017; Kansanga et al. 2020; Theis et al. 2019; Van Eerdewijk and Danielsen 2015 in Daum 2023). In Kenya and Ethiopia, one study found that women did not articulate their demand for mechanization within households, and were held back by a lack of control over resources as well as values, assumptions and intra-household decision-making dynamics (Van Eerdewijk and Danielsen 2015).

At times, the mechanization of women's activities has "simply" lagged. In some LMIC settings, "male" crops (often cash crops) and "male" activities (often more power-intensive ones like land preparation) have been mechanized before "female" ones (Doss 2001; Evers and Walters 2001; Sims et al. 2016). Moreover, the sequential mechanization of (power-intensive) activities typically performed by men followed by that of activities typically performed by women (control-intensive ones like weeding, harvesting and processing) has resulted in women taking on a greater share of household work. This has been observed in India and Nigeria, among other countries (Afridi et al. 2020, Takeshima and Lawal 2020, Doss 2001, in Daum 2023).

In the case of digital technology, there is evidence that adoption has not been equitable among farmers, and has been particularly weaker among women and older farmers. According to one survey on digital technologies in Sub-Saharan Africa, women accounted for an estimated 25% of registered users (although they accounted for 40-50% of farmers), while youth accounted for 70% (Tsan et al 2019). According to one study of leading digital platforms in Sub-Saharan Africa, only a fraction of their registered users – between 15-40% – have made active use of the services in question (Tsan et al. 2019). In many settings, women are less likely to get engineering, math or other technical degrees required for employment in technology sectors (including to develop and maintain machinery or digital services). Meanwhile, age and gender are not the only variables; skill and resource biases can also affect farmers' ability to access and benefit from digital technologies. **In that sense, just as digital technologies can help overcome certain resource gaps, their uneven uptake can also perpetuate and entrench those gaps**. For example, mobile money adopters in Mozambique, and early adopters in particular, were more educated than nonadopters, and were also more likely to already have a bank account (Batista and Vicente 2020).

Of course, even when farmers have initial access to a technology, they may be impeded from fully benefiting from it. For example, farmers may have access to a power tool but lack the means of refueling or repairing it for lack of liquidity or access to spare parts. They may have access to a mobile device but lack funds to pay for continued service or are unable to read and write text messages to access farming advice. In the context of information and advisory services, farmers may lack the means to act on what they have learned or been advised. They may not have access to recommended soil testing services, lack the storage infrastructure needed to postpone selling their products or may lack the time or prerogative to do business in a more distant market.

Because of adoption differences, technology has the potential to accentuate divergences among those with more or less power and means. Marginalized farmers can only benefit from mechanization and digitization if the technologies in question are available and accessible to them, and of course, adapted to their realities and needs. And given the game-changing nature of many technologies, not having access to or full use of them can drive a thick wedge between the outcomes of those with and without them. In this respect, historically marginalized groups risk falling further behind in contexts of accelerating

[22] These patterns are not evident everywhere. In China, female-headed households were more likely to use farm machines than male-headed ones (Ma et al. 2018).

technology adoption if their constraints to adoption – and the development of well-targeted technologies – are not proactively addressed with public and private sector involvement.

As already noted, there are settings where mechanization has had adverse equity effects among farmers by causing some to be displaced or underemployed. This scenario has seemingly been more likely to play out in settings where farmland is scarce, agricultural labor is abundant and wages are low, and above all, where technology adoption is ahead of market forces as a result of government intervention (Daum 2023). In Bangladesh, the adoption of powered milling reportedly resulted in the displacement and underemployment of women from low-income and landless households who typically offered more traditional milling services using a rented foot-operated mortar and pestle known as *dheki*. According to an earlier review of mechanization in Asia, adverse equity effects have almost invariably been observed in countries where mechanization has been "inappropriately" subsidized by the public sector (Pingali 2007) rather than driven by market forces. Mechanization has also been known to increase land competition and the displacement of small farmers in countries where agricultural land is scarce and, whether land is scarce or not, where their land rights are poorly established. For example, in Pakistan and Bangladesh, tractor use led to the displacement of tenant farmers during an earlier stage of agricultural development (Lockwood et al. 1983, McInerney and Donaldson 1975, Jabbar et al. 1983). In some countries where land is abundant, mechanized farms have been able to grow without direct immediate effects on non-mechanized farms (Houssou and Chapoto 2014 in Daum 2023). But in Ghana, mechanized farmers expanded by renting out less land to non-native farmers and appropriating communal lands (Kansanga et al. 2018).

However, according to one review of mechanization literature, the negative equity consequences of mechanization have not been as severe or widespread as sometimes presumed or expected. The study (Pingali 2007) observed that even in the labor surplus economies of Asia, the mechanization of power-intensive operations has had minimal effects on equity, at least where markets have been allowed to function with minimal government intervention. In the study, the ill fate of *dheki* operators in Bangladesh (described above) is meant to illustrate an exception more than the rule. In many cases, control-intensive operations like weeding have generally continued to be performed by human labor until wages have risen due to increased labor withdrawal from the agricultural sector. Equity concerns have also been less salient where mechanized farms have expanded by acquiring land from farmers who have voluntarily exited the farming profession as part of the structural transformation processes (Pingali 2007, Daum 2023). In Nigeria, tractors, "seem to be helping smallholders survive and become more productive, rather than inducing their exit from farming" (Takeshima and Lawal 2020, p. 446 in Daum 2023).

Institutional and technological innovations have, to an extent, helped mitigate the mechanization divide among farms of different sizes and capacities. In particular, the development of smaller machinery like two-wheel and small four-wheel tractors, small-scale processing equipment and hand-held power tools, as well as equipment rental and farming service markets and cooperative equipment sharing models, have enabled poorer farmers to mechanize (Berhane et al. 2020; Elverdin et al. 2018; Gulati and Juneja 2020; Takeshima 2017 in Daum 2023). In recent years, a number of asset-sharing and rental arrangements have leveraged digital tools, although it is not yet clear that digital technology can address the core constraints of these models.

Equipment rental and farm mechanization services have been one answer to the challenge of small farm mechanization. Renting equipment helps owners amortize it and nonowners access equipment they cannot afford. In Ethiopia, a new motor pump costs US $300-1,500, but pumps can be rented for US $0.80/hour plus fuel (Glatzel et al. 2019). Rental and service models – most of which are decentralized, self-organized, private outsourcing services provided primarily by rural machinery owners (Belton et al. 2021) – have been a major enabler of small farm mechanization across Asia, including in India (Bhattarai et al. 2017), China (Zhang et al 2017), Thailand (Cramb and Thepent 2020), Myanmar (Belton et al. 2021) and Bangladesh (Mottaleb et al 2017). In Bangladesh, rental options have been credited with the fact that, although 90% of farming households had under 1 hectare of farmland, 89% had adopted tractors or power tillers for land preparation (Bhattarai et al. 2020). In India, according to one study, rental markets have played a major role in making tractors, "accessible to all segments of farmers, including smallholding and marginal farmers" (Bhattarai et al. 2017). Equipment rental in India is offered by individual farmers, cooperatives and other joint ownership arrangements, rural entrepreneurs, large firms with large fleets of tractor fleets, as well as public-private and purely public hire centers.

In recent years, a number of asset-sharing and rental arrangements have sought to leverage digital tools to mitigate the costs and inefficiencies that sometimes hamper rental markets. However, it is not yet clear that digital technology can address the core constraints of these models (Box). A key challenge of equipment rental and sharing models is that farmers in a given area all want to use the same equipment at the same time, and have little use for it at other times of the year. Some businesses have overcome this challenge by diversifying the geographic areas and crops they serve to take advantage of their differences in seasonality. Rental markets have also been undermined by high (transaction) costs where infrastructure is poor and farms are small and fragmented (Daum and Villalba et al. 2021). In Zambia, one study found that only half of tractor owners who purchased tractors to serve smallholder farmers offered services (Adu-Bafour et al. 2019).

Box 6: "Uberization" of tractors: the potential limitations of leveraging digital technology to facilitate smallholder mechanization

Equipment sharing or "uberization" models like Hello Tractor and EM3 in India have tried to leverage digitization to increase small farmer access to farm equipment. In the case of Hello Tractor in Nigeria, the service can be requested via a smartphone application. However, few Nigerian smallholder farmers own smartphones. In 2018, approximately 13% of the population across urban and rural areas owned smartphones (Kooistra 2018). Moreover, those who own phones rarely trust them to make transactions (Foote 2018 in Daum and Villalba et al. 2021b). Realizing this challenge, Hello Tractor established a network of booking agents who create awareness about tractor availability and pool the demand from individual farmers or cooperatives in a particular area for a 10% commission (Jones 2018 in Daum and Villalba et al. 2021b). As such, it is reported that most farmers rely on the help of a booking agent. While potentially effective, this adaptation has likely eroded the cost-advantage of digital service booking. That said, the digital interface continues to play a central role I keeping search costs low and enabling equipment owners and users to connect.

In some contexts, in lieu of purchasing or even renting equipment, farmers can hire mechanization services. This model is particularly developed in China, where it has become common for small farms to pay companies for mechanized plowing, sowing, irrigation, crop protection, spraying and harvesting services. Since 2016, some 84% of rural villages and tens of millions of farmers have used an estimated 200,000 mechanization service companies, which were developed in response to a combination of rising wages and state subsidies. Often provided by individual farmers, and at times provided by farmer machinery cooperatives or machinery companies serving a wider area, service companies have reportedly played a major role in China's agricultural mechanization (Zhang et al. 2017, Deng et al. 2020, Huang 2021). In Myanmar, the use of tractors for land preparation and combine harvesters for harvesting and threshing is reportedly only marginally higher among larger farmers due to the country's vibrant service markets (Daum 2023; Belton et al. 2021). Mechanization took off rapidly in the country following economic and political reforms in 2011, and most mechanization is thought to have been enabled by rental and mechanization services offered by individual farmers and small enterprises (Belton et al. 2018; Belton et al. 2021).

An important way machinery rental and service models can help address inequities is by enabling smaller and less well-off farms to partake in the nonfarm economy. In China, mechanization services have contributed to reducing income inequality among rural households by enabling lower-income households to partake in the nonfarm economy (Sang et al. 2023). Interestingly, mechanization services have contributed significantly more to closing rural income gaps in parts of China where nonfarm economic opportunities are more developed. Meanwhile, mechanization services have not had a significant effect on income derived from farming activities themselves (Sang et al. 2023), although a variety of studies have shown mechanization services to improve farm efficiency and productivity, in addition to facilitating labor transfer to other sectors of the economy (Zhang et al. 2017; Zhang et al. 2020; Deng et al. 2020).

The organization of rental markets illustrates how the public sector is not always needed and can sometimes be the most helpful by playing a limited, focused role. There are countries where governments have helped facilitate the organization of rental markets to varying degrees or provided rental services directly. For example, public-private partnerships have facilitated the distribution of machinery and the provision of support services in the Philippines, and Thailand has implemented successful custom hiring centers (Bhattarai et al. 2020). As noted, some machinery rental services in India are spearheaded by or backed by the government, although the development of custom hire services and markets have mostly emerged with little direct government support in profitable farming areas (Bhattarai et al. 2020). In Nigeria, public hire centers offering tractors were considered inefficient and often abandoned during the 1980s (Akinbamowo 2011 in Takeshima in Lawal 2018, in Daum and Villalba et al. 2021). However, these were revived as public-private partnerships known as agricultural equipment hiring enterprises (AEHE) during the 2000s, with the public sector supporting private entrepreneurs (such as farmers, cooperatives and investors) with subsidized tractors (Takeshima and Lawal 2018 in Daum and Villalba et al. 2021). In Myanmar, where a vibrant rental service market has played a pivotal role in facilitating smallholder mechanization, public rental services are seldom used (Win et al. 2020). As noted, in China the government has subsidized the purchase of farm machinery destined for the provision of mechanization services (Huang 2021), but the provision of these services has been driven by the private sector.

2.5 Prospective Risks of Digital Platforms for Farmer Incomes and Income Inequality

When and how might digital platforms pose a risk to farmer incomes going forward? When and how might they exacerbate income inequality going forward?

KEY OPPORTUNITIES	KEY RISKS
• Policies and programs support digital connectivity, literacy and trust, with a focus on farmers and rural areas. • Farmers can choose to use digital services outside the scope of a donor project and are willing to pay for them. • Digital services give farmers access to extension and advisory services that they previously did not have access to, or improve their relevance and quality. • Platforms can bundle services and enable farmers to act on information and advice. For example, digital advisory services improve access to relevant inputs, equipment, finance, services and markets. • Farmers can organize and strengthen their position to make use of production and marketing data/advice.	• Competition is undermined and leads 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 in ways that are unwanted or do not coincide with their best interests. • Inequality increases if farmers lack the capacity to benefit from technology or the profiting of their data.

One prospective concern with digitization revolves around its potential to detract from farmer incomes in a specific set of circumstances. Those circumstances involve digital technologies undermining competition or narrowing farmers' access to information, markets, options and overall market power, or inducing them to make poor purchase and other decisions, particularly in the presence of digital platforms that exhibit strong network and lock-in effects.[23]

Digital services and platforms can give rise to what are known as network and lock-in effects. A network effect occurs when the value of a good increases with the number of parties using it. This applies to many digital services and platforms. Network effects often go hand-in-hand with lock-in effects, as these effects tend to reinforce each other. A lock-in effect exists when switching from one product or service to another is inhibited by its cost. Lock-in effects can reinforce network effects by driving users to the same product. And network effects can reinforce the lock-in effect by increasing the performance and value of the initial product and undermining the supply or performance of alternatives. The reach and intensity of these effects can be augmented when platforms encompass an increasing range of complementary goods and services, like when they bundle offerings or develop an entire ecosystem of online commerce or exchange. Other factors contributing to lock-in effects include farmers' lack of legally secured and enforceable rights over their data, a weak bargaining position to negotiate access to their data with big machinery or digital actors, as well as a lack of interoperability, compatibility and universal data standards (Atik 2022 in Hackfort 2023). In other words, the power platforms have over end users may be enhanced

[23] Digital platforms are not the only risk to competitive markets, and issues can arise in the context of mechanization as well. However, their effect is expected to be less systemic.

by (1) the bundling of services, and (2) the unregulated, unchecked and sometimes unwanted collection and use of user data.

While there is value to these platforms – so much so that they become unavoidable – they are also associated with a number of risks. The core issue is that these platforms give their owners a great degree of control over who gets to participate and the rules of exchange. If left to their own devices (unregulated or unchecked), such platforms can lead to a narrowing of choices and competition, and the exclusion of certain players from certain markets. Recent studies show how the digital economy is characterized by concentrated corporate power and monopoly-like situations through lock-in effects, and that these structures are associated with control over digital technology, the distribution of benefits and value generated from data (Srnicek 2017 in Hackfort 2023).

In the context of agriculture, digital platforms have the potential to develop in such a way that they cause a loss of competition in input or output markets, leading to higher costs or lower revenues for farmers and negatively affecting their profitability. This scenario may be especially likely to arise in the context of digital platforms that bundle services or lure farmers into a web of integrated or interconnected services that crowd out competition. Farmers may find themselves beholden to suppliers and/or buyers that are strongly coordinated, providing farmers inputs, credit, insurance and buying their products, all while using data to assess their creditworthiness or risk-profiles, and so forth. The potential for digital platforms to create lock-in effects in the context of agriculture is founded. For example, in high-income countries, some large agribusiness companies have sought to leverage farm management software to drive users to their products (inputs), using the data generated by the platform to optimize these products and designing products that drive users to continue using the inputs and platform together as a packaged service.

There could be a fine line between the benefits and risks offered by digital platforms. By collecting data on farmers and leveraging advanced data analytics, platforms may open the door to asset-poor farmers (including women with no land, financial history, collateral or formal education) to access financial services, including credit and insurance, and improved inputs and advice for the first time. Moreover, gaining access to these goods and services could potentially transform their lives in desired ways. However, it is possible to imagine scenarios in which farmers are excluded from access to services or entire markets on the basis of opaque datasets and algorithms, with little recourse or alternatives. Over time and at scale, such platforms, if unchecked, could potentially enable undue control over farmers and entire ecosystems of knowledge, product and service providers, potentially harming farmers with limited means to understand risks or protect themselves. Platforms could also potentially (intentionally or unintentionally) exclude certain knowledge and technology (like indigenous and agroecological) from circulation for a lack of commercial backing or value.[24]

Digital technology introduces the possibility of turning farmer data into a lucrative resource, but does not automatically give farmers the means to profit from that resource. As discussed, farmers may be able to (marginally) increase their profitability by using digital services that help them optimize how they manage their farm or sell their products. But farmers often do not benefit fully or at all from the (potentially large) returns on the data generated by software providers to whom they release their data. In some cases, farmers pay low or no fees to access digital platforms and “pay” to access them by agreeing to relinquish their data, either knowingly or unknowingly. Technology providers can then use

[24] A closely related set of risks lies in the release and use of large quantities of user data. The risk lies particularly in the use of data by commercially motivated players to influence user choices, including their purchase decisions or access to products. The issue is salient in the context of advertising-supported digital services, but the potential for users to be influenced exists even in contexts where that influence is not directly embedded in the digital service through which user data is released. Data can be used to develop, promote, price or determine access to complementary products, or more broadly, for design, underwriting, marketing and cross-selling purposes. In these instances, data analytics (and artificial intelligence) can be used in ways that align with user interests, helping to fine-tune products to users’ bona fide needs or make them accessible in the first place (for example, enabling access to finance or insurance by substituting data for a lack of collateral). However, commercial uses of data are driven by the profit motive and can fall out of alignment with the “reasoned” interests of uses. They can also become biased and discriminatory.

the data from large numbers of farms to perfect and develop new products, astutely market them and increase their sales and profitability. In some cases, they may sell farmer data to other companies positioned to make use of it. With little insight into the aggregate value of their data, and in any case, little power to act on that knowledge, farmers often profit little, if at all, from their data.

A missed opportunity to increase farmer incomes and decrease inequality may lie in enabling them to share the commercial profits derived from the use of their collective data. From that perspective, some see promise in the development of open-source platforms that, at least in theory, give farmers control over how their data is used. Examples of initiatives thinking along these lines and trying to develop low-cost, open-source platforms under the control of farmers (versus agrifood or tech companies) include FarmOS, the OpenAg Data Alliance, Joindata, FarmLogs and DJustConnect (Hackfort 2021). However, most farm workers are completely unequipped to do this (that is, derive profit from their aggregated data) in most places and have no pathway to get there[25]. Truly empowering development would enable farmers to share in the profits the companies serving them generate, including or especially technology providers. Farmer ownership and control of insights derived from their data could be game changing. State intervention would likely be needed to enable this scenario, with the risk being that interventions of this type could undermine the profit potential driving technological innovation.

[25] These questions are discussed at some length in Van Geuns et al. 2023.

3. A Framework for Context-Informed Action

The best way to spread the benefits and mitigate the risks of technology is bound to vary across contexts. Indeed, the research underlying this paper covers a wide range of Asian and African contexts in which agricultural machinery and digital tools have been adopted. And those contextual factors often have a bearing on the pace and inclusiveness of technology commercialization and adoption, the nature and magnitude of adoption benefits, the types of risks the technology introduces and the capacity to mitigate those risks. Just as contextual factors can influence adoption rates and associated opportunities and risks, they also point to different sets of actions that can or must be taken to spread the benefits and mitigate the risks of mechanization and digitization. LMIC agriculture and rural economies are highly heterogeneous; a one size fits all strategy is inappropriate for tackling pertinent challenges and pursuing available opportunities.

There are many relevant contextual factors, although these can be grouped into a few categories. One relates to *policy environment*, which can be shaped by national agricultural development strategies and their emphasis on technological change, and national policies relating to land, access to finance, industry, trade, intellectual property, labor and others. A second category relates to *rural infrastructure* like electricity, telecommunications, access roads and market infrastructure. The functioning and vibrancy of various *markets* – for land, labor, agricultural inputs and commodities – represents a third category of relevant factors. A fourth category relates to the *rural institutions and ecosystems* that bring everything from policies to markets to life. Finally, the *assets and capacities of farmers* and rural communities are also important factors; for example, levels of education, skills, landholdings and degree of organization for collective action. While it is possible to quantify or benchmark different contextual factors, it is not obvious how one would assign them (relative) weights in their aggregation.

A more tangible way of distinguishing contexts amid the heterogeneous landscape of LMIC agriculture is to subdivide country (or subnational) settings according to their stage of agrifood system transformation. There is rich and growing literature on this subject, which employs a variety of variables to inform the classifications. At a country level, agrifood transformation is typically a long (multi-decade) process involving changes, among other things, in what is produced, how it is produced, how production and value chains are organized, how the system is supported and regulated, what society expects from it and how performance is measured.

For the purpose of this analysis, three main agrifood system settings are distinguished: traditional, transitioning and modernizing. The characteristics of these settings, along with their central technology-related challenges and opportunities, are briefly summarized below and in **Error! Reference source not found.**. These descriptions set the stage for identifying how private sector actors can help spread the benefits and mitigate the risks of technology.

Traditional agrifood systems

Some countries or areas in an early phase of agrifood system transformation have what are called *traditional agrifood systems*. In these settings, agriculture remains a leading source of employment and rural incomes, and much agrifood commerce remains localized or involves informal channels, typically with multiple layers of intermediaries. Some demographic and socioeconomic shifts are occurring, but these bring about still limited change in farming practices, specialization or labor market participation. In this early phase, agricultural mechanization and digitization are generally proceeding at a very slow pace against a backdrop of weak public infrastructure, policy and regulatory environments, and slow agricultural commercialization. This type of setting is found in many low-income countries and remote or lagging regions of lower middle-income countries.

In traditional systems, technology adoption may be occurring among small clusters of more successful farmers in particular value chains or ones involved in a pilot or development project. In traditional agrifood systems, most of the opportunities to effectively use machines and digital tools for productivity, quality, income or risk management gains remain unavailable. The biggest technology-related risks in these settings relate to (1) overzealous public promotion (and wasted public resources) in the face of insufficient demand; and (2) failure to lay the necessary foundations for mostly forthcoming mechanization and digitization, in terms of awareness, policies and infrastructure. With only selective adoption, risks associated with equipment misuse are low, concerns about inequitable adoption are largely premature and there is little risk or concern for anti-competitive practices in the digital services realm.

Transitioning agrifood systems

Other places have *transitioning agrifood systems*. These settings are in the throes of accelerating change – including in diets, land use, value chain organization and technology – against the background of an improving enabling environment. In many such settings, agricultural employment is declining, and many rural households are increasingly relying on nonfarm income, which in many cases is lifting their living standards and overall resilience. These trends are common in lower middle-income countries, and sometimes on display in the lagging agricultural areas of upper middle-income countries, as well as in more advanced (and typically export-oriented) agricultural clusters in low-income countries.

In transitioning agrifood systems, technology adoption ramps up as market building gains steam and technology providers learn how to better match equipment, services and business models to farmer needs, circumstances and habits. The range of technology applications is steadily increasing. However, many farmers still face financial, social and other barriers to accessing and making full use of technology, including at times a lack of collective organization. In the course of mechanization, some (landless) agricultural workers may see reduced work opportunities. With large numbers of farmers newly taking up machines and digital tools, and many technology and related service providers navigating new territory, there are also likely to be some transitional safety and servicing challenges.

Modernizing agrifood systems

A third type of setting have what are known as *modernizing agrifood systems*. By this phase of agrifood system transformation, agriculture's share of employment, rural incomes, GDP and trade have leveled off or stabilized. That said, major changes are still afoot in labor markets and rural institutions, farms are typically undergoing consolidation and value chains are formalizing. These trends are found in most well-connected regions of upper middle-income countries and in the most dynamic rural clusters of lower middle-income countries.

In these settings, technology adoption has typically occurred at scale against a backdrop of quite strong infrastructure and policies, and a higher degree of agricultural commercialization. The technologies in question are being mainstreamed into value chain operations and the breadth of technology adoption begets further opportunities to improve technology offerings and better serve farmer needs, offering ripe terrain for technology and business innovation. At the same time, unintended consequences of technology adoption also start to play out or become more apparent, calling attention to challenges in areas ranging from worker safety and environmental protection to data security and competition. In these settings, some residual problems with inequitable access to technology persist.

Table 2: Stages of Agrifood Transformation: Selected Indicators of Change

Indicators of Change (Examples)	Traditional	Transitioning	Modernizing
Agriculture's Share in Total Employment and Rural Income	Higher	Moderate	Lower
Agriculture's Share in Rural Household Income	Higher	Moderate	Lower
Agricultural Intensification and Diversification	Lower	Moderate	Higher
Labor Intensity of Production	Higher	Moderate	Lower
Level/Rate of Agricultural Mechanization and Digitization	Lower/Slower	Moderate/ Accelerating	Higher/Substantial
Mix of Informal/Formal Distribution Channels	80%-20%	60%-40%	30%-70%
Land Tenure Security	Lower	Moderate	Higher
Gender Equality	Lower	Moderate	Moderate
Infrastructure Access (e.g., Electricity and Improved Roads)	Lower	Moderate	Higher
Access to Formal Financial Services	Lower	Moderate	Higher
Rural Education Attainment	Lower	Moderate	Higher
Rule of Law and Ease of Doing Business	Lower	Moderate	Higher

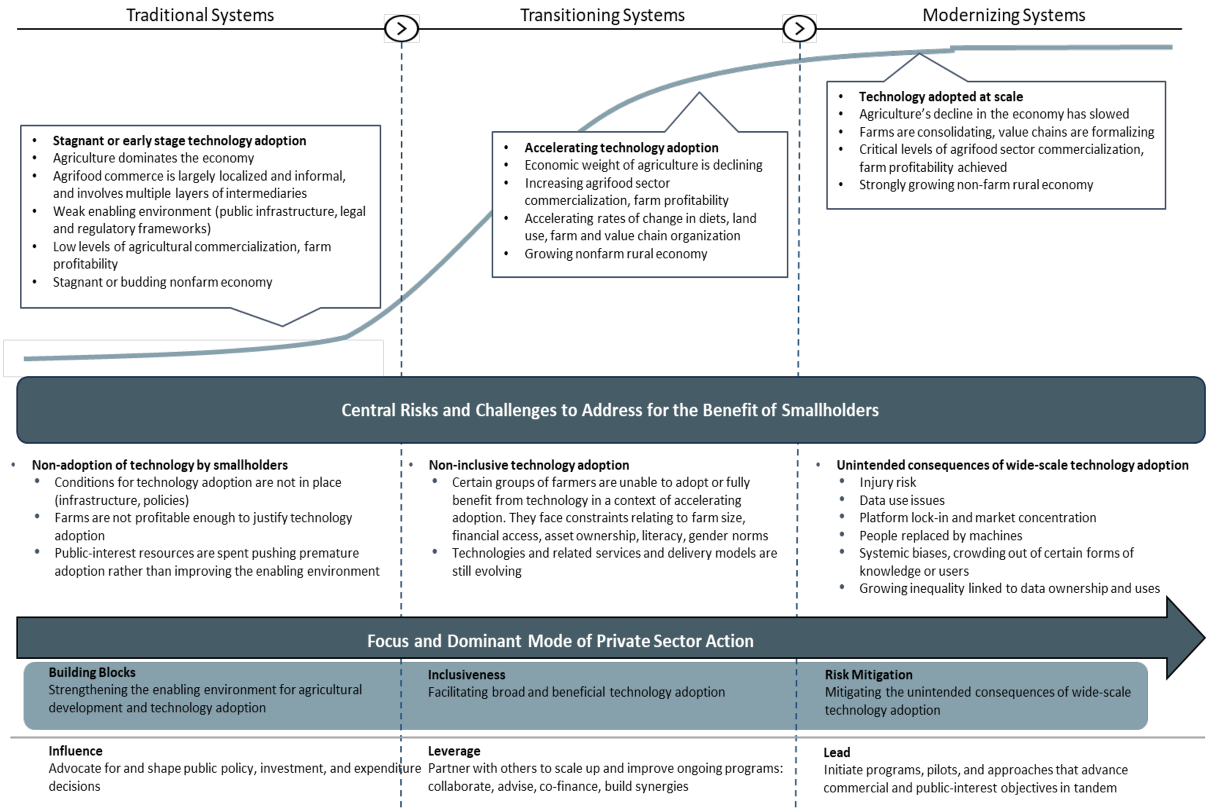
Within the different contexts in which agricultural mechanization and digitization are occurring, there are different ways the private sector can help spread the benefits and mitigate the risks of technology. What the private sector does, how it goes about doing this and with whom it interacts or partners can take different forms, the relative weight of which is bound to vary across settings. Schematically, three modes of private sector action are distinguished: lead, leverage and influence (Box 7).

Box 7: Three modes of private sector action

- *Lead*: In this mode, the private sector directly invests, provides specific services and applies given business practices. In this case, the private sector may supply technology directly or incorporate it into value chain operations.
- *Leverage*: In this mode, the private sector works or partners with other stakeholders – like government entities, NGOs and development agencies – to scale up and improve ongoing programs. This mode may involve collaboration, advisory work, direct investment and co-financing.
- *Influence*: In this mode, the private sector acts as an advocate and advisor, shaping public policy, investment and public expenditure decisions.

Combining the two dimensions described above – differentiating settings and modes of action – the following framework offers a schematic view of technology-related opportunities, risks and pertinent interventions. The framework, described next, is summarized in **Error! Not a valid bookmark self-reference.**, identifying the opportunities, challenges, risks and roles of business across the different types of settings.

Figure 7: Potential Roles of Business in Addressing the Opportunities, Challenges and Risks of Technology in Different Agrifood System Settings



In traditional agrifood systems, where technology adoption is at an early stage, the central focus is on establishing the building blocks for market-led mechanization and digitization. They include investment in basic rural and agricultural infrastructure; the adoption and implementation of policies and regulations that support agricultural sector productivity, commercialization and development at large; and programs supporting early adopters of technology and service providers. Hence, the scope for private sector action lies primarily in influencing efforts by the public sector, as well as shaping and supporting public policies, investments and initiatives. (Some commercial opportunities may be available, creating early opportunities to demonstrate responsible business practices.)

In transitioning contexts, where technology adoption is taking hold or accelerating, the core focus is on fostering inclusive and effective technology adoption and market building. In this phase, the scope and need for private action is significantly widened, yet centers around leveraging existing initiatives and partnership opportunities. It includes the direct provision and servicing of technology on a commercial basis, and the participation in joint efforts – including public-private ones – to address the risks of both technology adoption and the exclusion of certain farmers or groups thereof. Gender-informed programs would be key in many countries, as would efforts to strengthen collective farmer action and financial access. There is also a continued need to improve the enabling environment for agriculture and technology adoption in these settings, and hence, to influence and support ongoing policy, infrastructure and institutional development efforts.

In modernizing contexts, where technology adoption has occurred at scale, leading further technology innovation and market development is a priority, with an increasing focus on risk mitigation. In these settings, private sector action can focus more on mitigating occupational health and safety risks presented by machinery use, the environmental damage potentially associated with mechanization-assisted agricultural extensification and an array of digital risks, from anti-competitive practices to data-use ones.

Table 3 (on mechanization) and

<table>
<tr><th></th><th>Traditional</th><th>Transforming</th><th>Modernizing</th></tr>
<tr><td rowspan="7">Lead</td><td colspan="2">Invest in machinery that not only improves efficiency, but also occupational safety.</td><td></td></tr>
<tr><td colspan="2">Align technology offerings with the needs/capacities of smallholder farmers.</td><td></td></tr>
<tr><td colspan="2">Engage in responsible marketing/sales to discourage children’s use of machinery.</td><td></td></tr>
<tr><td></td><td colspan="2">Implement equipment rental or sharing programs and establish strong local repair and service systems via local companies.</td></tr>
<tr><td></td><td colspan="2">Co-finance and technically support programs developing mechanization-related agro-entrepreneurship.</td></tr>
<tr><td></td><td colspan="2">Support homegrown manufacturing capacities, where this can be done competitively.</td></tr>
<tr><td colspan="3">Avoid reinforcing gender stereotypes and biases in the design and marketing of technologies.</td></tr>
<tr><td rowspan="7">Leverage</td><td colspan="2">Participate in programs demonstrating the benefits of technology to early adopters.</td><td></td></tr>
<tr><td>Help improve the enabling environment. Co-finance public infrastructure and human resources.</td><td></td><td></td></tr>
<tr><td colspan="2">Provide training programs on equipment use and maintenance for farmers.</td><td></td></tr>
<tr><td colspan="2">Support financial access and self-help or collective action programs that widen farmer access to mechanization equipment or services.</td><td></td></tr>
<tr><td colspan="3">Promote gender equality in technology access, addressing cultural perceptions and marketing practices that hinder access or dissuade use.</td></tr>
<tr><td></td><td>Collaborate in public-private programs offering vocational training and developing alternative livelihood opportunities for unskilled farm workers who are at risk of seeing their labor replaced by machines.</td><td></td></tr>
<tr><td></td><td>Support public-private measures to ensure that mechanization improves occupational health and safety by developing or advocating for the adoption and enforcement of industry safety standards, and offering training and licensing for machine operators.</td><td></td></tr>
<tr><td rowspan="5">Influence</td><td>Advocate for investments in relevant public infrastructure.</td><td></td><td></td></tr>
<tr><td>Advocate against aggressive subsidization of machinery.</td><td></td><td></td></tr>
<tr><td colspan="2">Support the establishment of industry standards and guidelines for occupational health and safety.</td><td></td></tr>
<tr><td></td><td>Support policy reforms, programs and services that facilitate land transfer while safeguarding farmer land rights and natural ecosystems.</td><td></td></tr>
<tr><td></td><td colspan="2">Raise awareness about and guard against the risk of land expropriation, farmer displacement and encroachment into natural</td></tr>
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<table>
<tr><td></td><td></td><td colspan="2">landscapes potentially associated with mechanization-enabled extensification.</td></tr>
</table>

Table 4 **(on digitization) provide a more detailed list of activities businesses can undertake at each phase of agricultural transformation.** A longer list of possible public and private sector interventions can be found in Annex 1.

Table 3: Mechanization – Private Sector Actions to Spread Benefits and Mitigate Risks

<table>
<tr><th></th><th>Traditional</th><th>Transforming</th><th>Modernizing</th></tr>
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<tr><td></td><td colspan="2">Raise awareness about and guard against the risk of land expropriation, farmer displacement and encroachment into natural landscapes potentially associated with mechanization-enabled extensification.</td></tr>
</table>

Table 4: Digitization – Private Sector Actions to Spread Benefits and Mitigate Risks

<table>
<tr><th></th><th>Traditional</th><th>Transitioning</th><th>Modernizing</th></tr>
<tr><td rowspan="5">Lead</td><td colspan="2">Establish good practices for user risk-profiling for the provision of financial services, and monitor and guard against systematic bias.</td><td></td></tr>
<tr><td></td><td>Leverage digital tools to facilitate access to services like extensions and finance among women and other underserved farmers.</td><td>Explore/support business models that give smallholder farmers a path to co-ownership of technology, data and related profits, and enables them to shape the directions in which technology develops, as well as to profit-share.</td></tr>
<tr><td></td><td colspan="2">Facilitate the bundling of digital services to enhance farmer access to information, knowledge and markets, while guarding against an erosion of competition.</td></tr>
<tr><td></td><td colspan="2">Ensure data privacy and security. Educate farmers and the public about digital security while developing recourse mechanisms for digital users (in case of exclusion from service, algorithm errors or other unforeseen situations).</td></tr>
<tr><td></td><td></td><td>Uphold data release and use restrictions by refraining from the release of certain types of data and certain uses of released data.</td></tr>
<tr><td rowspan="5">Leverage</td><td></td><td colspan="2">Facilitate farmers’ collective action relating to the use of digital opportunities, such as e-commerce and others, while building their capacity to fully benefit.</td></tr>
<tr><td></td><td colspan="2">Leverage digital tools to monitor and enhance worker health and safety, as well as supply chains for labor rights violations.</td></tr>
<tr><td colspan="2">Collaborate in programs to support digital connectivity, literacy and trust.</td><td></td></tr>
<tr><td></td><td colspan="2">Collaborate in programs to address digital access and literacy gaps among specific farmer groups.</td></tr>
<tr><td></td><td colspan="2">Support efforts to drive worker recruitment to platforms that screen recruiters and provide job seekers information about their rights.</td></tr>
<tr><td rowspan="5">Influence</td><td colspan="2">Support policies promoting public or public-private investment in telecommunications and digital infrastructure.</td><td></td></tr>
<tr><td colspan="2">Advocate for policies that strengthen the property rights of women and promote gender equity in technology/finance access.</td><td></td></tr>
<tr><td colspan="2">Advocate for public sector efforts to develop the building blocks of digital agriculture, including the digitization and interoperability of various databases and information systems, the development of digital farmer registries and more.</td><td></td></tr>
<tr><td colspan="3">Collaborate in multi-stakeholder processes seeking to develop or update national (agricultural) digitization strategies or other related policies (or bringing agriculture into the fold of cross-cutting digitization strategies).</td></tr>
<tr><td></td><td colspan="2">Support the development and implementation of an accreditation, licensing and regulatory surveillance system for agri-e-commerce providers.</td></tr>
</table>

		Support the development of a regulatory system promoting competition and preventing abuses of market power stemming from digital platforms. This would include provisions on data privacy, security, use, release and disclosure, anti-competitive practices, the use of information for risk-profiling and so forth.

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