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Agricultural mechanization and sustainable agrifood system transformation in the Global South

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The State of Food and Agriculture 2022

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Abstract

Agricultural mechanization has enabled many societies across the world to decouple agricultural production from agricultural labour, freeing them from the heavy physical toil of farming, but there are large disparities between the Global North and the Global South. This paper provides an overview of the state of agricultural mechanization across the Global South – i.e. Eastern and South-eastern Asia, Southern Asia, sub-Saharan Africa, Latin America and the Caribbean – and explores the potentials and risks of agricultural mechanization for the sustainable transformation of agrifood systems. Many – but not all – Asian and Latin American and Caribbean countries have experienced considerable progress regarding mechanization, driven by farming system evolution, structural transformation, and urbanization. While progress in sub-Saharan Africa has generally been more limited, farming systems have been rapidly evolving and mechanization has emerged as a top policy priority.

Findings suggest that agricultural mechanization can help make agrifood systems more sustainable due to positive effects including, but not limited to, labour productivity, poverty reduction, food security, health, and well-being. Possible trade-offs concern unemployment effects, biodiversity loss, land degradation, and growing disparities between large and small farms, among others. A wide range of technological and institutional solutions is identified to harness the potential of agricultural mechanization for sustainable agrifood system transformation, while at the same minimizing the risks.

Keywords: Agricultural mechanization, automation, agrifood systems, transformation, robots, Global South.

JEL codes: Q16, Q18, O57.

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1 Introduction

Agricultural production has bound the majority of humanity to the land since the earliest times, occupying much of their physical and intellectual resources. This type of life was often associated with drudgery, hunger and poverty (Mazoyer and Roudart, 2006). Agricultural history shows how humankind has constantly strived to reduce the toil of farming by developing ingenious tools and by harnessing the power of fire, wind, water and animals. For example, Mesopotamia farmers used ox-drawn ploughs by around 4000 BCE (Mazoyer and Roudart, 2006) and water-powered mills emerged in China by around 1000 BCE (Pingali, 2007). Technological change has accelerated during the past two centuries, triggered by the discovery of steam power, the emergence of steam threshers and ploughs by the mid-nineteenth century, and later the rise of fossil energy-powered tractors, harvesters and processing machines, among others (Daum, Huffman and Birner, 2018; Hurt, 1982). Agricultural mechanization has enabled societies across the world to gradually decouple agricultural production from agricultural labour, freeing them from the heavy physical toil of farming. With the rise of automation, which can render a previously manual process partially or entirely automatic and therefore substitute both physical and mental work, this decoupling nears completion.

Progress has not been even across the world. Agrifood systems in Northern America and Europe are fully mechanized and partly automated. Many – but not all – Asian, Latin American and Caribbean countries have made considerable progress regarding mechanization and automation plays a growing role in parts of agrifood systems (Diao, Takeshima and Zhang, 2020). In sub-Saharan Africa, progress towards agricultural mechanization has on the whole been limited, despite signs of rapid mechanization in selected pockets (Daum and Kirui, 2021; Daum and Birner, 2020; Diao *et al.*, 2014; Diao, Takeshima and Zhang, 2020). In sub-Saharan Africa, around 80 percent of farmers are believed to rely on manual labour (FAO and AUC, 2018). This unequal progress towards mechanization explains the dramatic differences in agricultural labour productivity across the world, which in turn helps to explain world income inequality (Fuglie *et al.*, 2019; Gollin, Lagakos and Waugh, 2014). The agricultural value-added per worker in Northern America is 66 times higher than in sub-Saharan Africa, 51 times higher than in South Asia, 10 times higher than in Eastern Asia and the Pacific, and 15 times higher than in Latin America and the Caribbean (World Bank, 2022). While farmers in the United States of America obtain 1 470 kg of maize per hour worked, Kenyan farmers obtain only 1.2 kg (Gollin, 2019).

Agriculture plays a key role in the quest for sustainable development – as formulated in the 17 Sustainable Development Goals (SDGs) of the United Nations. However, agrifood systems are often not economically, socially or environmentally sustainable (Antle and Ray, 2020). In the Global South (i.e. Eastern and South-eastern Asia, Southern Asia, sub-Saharan Africa and Latin America and the Caribbean), low land and labour productivity often cause hunger and poverty among farmers (Fuglie *et al.*, 2019; Sibhatu and Qaim, 2017; World Bank, 2020). Moreover, the high drudgery of manual farming undermines health and well-being (Daum and Birner, 2021; Ogwuike *et al.*, 2014). In the tropics, such effects will be exaggerated with climate change (Dasgupta *et al.*, 2021). Much of the high workload of farming is shouldered by unpaid family work, including women and children (FAO and IFPRI, 2021; Lowder, Sánchez and Bertini, 2019). 70 percent of child labour is in agriculture, affecting the present and future livelihoods of 112 million children (ILO, 2021).

Innovations around agricultural mechanization come with many promises to improve both productivity and labour conditions. Mechanization promises to raise agricultural labour productivity, a major determinant of income and poverty (Binswanger, 1986; Diao, Takeshima and Zhang, 2020; Fuglie *et al.*, 2019; Hayami and Ruttan, 1970; Sims and Kienzle, 2006). Mechanization also promises to reduce the high workload of farming (Daum and Birner, 2021; Ogwuike *et al.*, 2014; Sims and Kienzle, 2006). This may free up time for adults to pursue off-farm work, care activities and food preparation (Diao, Takeshima and Zhang, 2020; Johnston *et al.*, 2018) and for children to play and go to school (Daum, Capezzone and Birner, 2021; FAO and IFPRI, 2021). Furthermore, mechanization also has the potential to raise land productivity by allowing for more timely and careful crop management (Baudron, Nazare and Matangi, 2019; Daum and Kirui, 2021; Diao *et al.*, 2014; Silva *et al.*, 2019). Beyond the farm, processing, preserving, storage and transportation technologies promise to reduce food loss, enhance food safety and enable value addition (Daum and Kirui, 2021).

Mechanization's transformative power has also raised concerns. One fear is that large and wealthy farms are more likely to afford the necessary machines and then grow at the cost of smallholder farmers or tenant farmers (Daum and Birner, 2020; Pingali, 2007). A longstanding concern is that mechanization causes rural unemployment, which would undermine SDG 8 on decent work (Binswanger and Donovan, 1987; Daum and Birner, 2020). There are also concerns that (on-farm) mechanization can undermine environmental sustainability and resilience by contributing to deforestation, savannah conversion, farmland simplification, biodiversity loss and land degradation (Daum *et al.*, 2020; Daum and Birner, 2020).

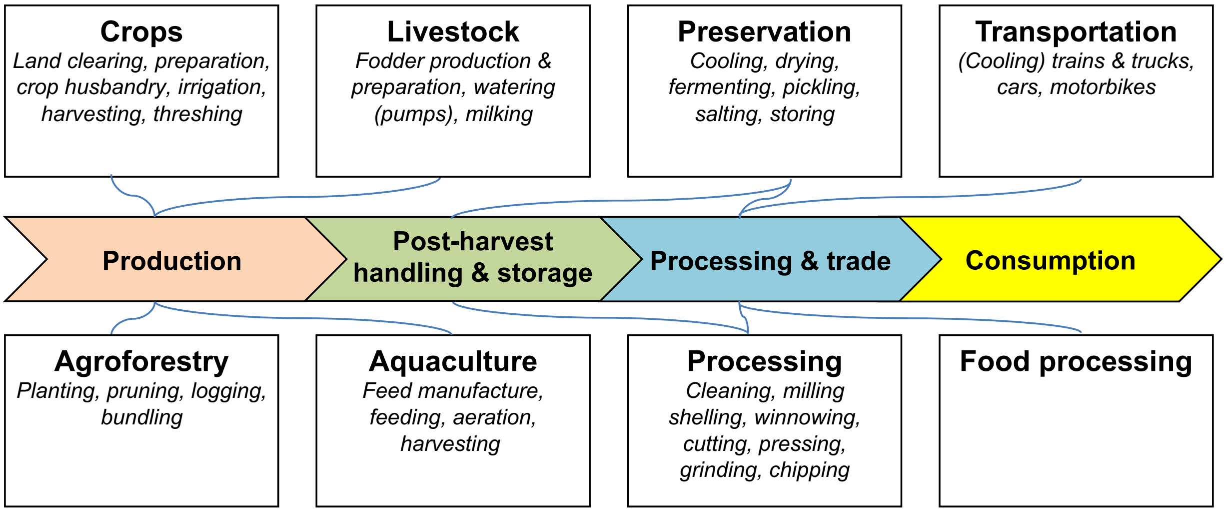
Understanding sustainability synergies and trade-offs are key to guiding and designing policy action that will harness the opportunities and mitigate the risks associated with mechanization. This paper therefore aims to contribute to a better understanding of the progress, opportunities and risks related to agricultural mechanization and its role in sustainable agrifood system transformation in the Global South. The paper will answer questions such as: Why has the progress towards mechanization and automation been more limited as compared to the Global North? Why have some regions within the Global South witnessed more progress towards mechanization than others? What are the barriers to adoption in some countries? What are the opportunities and risks associated with mechanization? Should policymakers actively promote mechanization? What can they do to harness the potential of mechanization, while safeguarding against some of its threats?

Section 2 will provide an overview of some key definitions and terms related to agricultural mechanization to equip the reader with the necessary vocabulary for this paper. Section 3 will provide an overview of the trends of agricultural mechanization in the Global South, focusing on Asia, Latin America and the Caribbean and sub-Saharan Africa. Section 4 discusses some major drivers of mechanization as well as adoption barriers undermining mechanization, i.e. for smallholder farmers. Section 5 explores the opportunities and risks of agricultural mechanization for sustainable agrifood system transformation. Section 6 focuses on the role of technological and institutional innovations to make agricultural mechanization inclusive for smallholder farmers. Finally, Section 7 concludes and provides policy recommendations on how to create an enabling environment for agricultural mechanization and ensure it contributes to sustainable agrifood system transformation.

2 Definitions and key terms

This paper defines agricultural mechanization as the substitution of human labour with animal or mechanical power in agricultural production, handling and processing in the crop, livestock aquaculture and agroforestry value chains (Daum and Kirui, 2021). While some define basic hand tools to be part of mechanization, for the purpose of this analysis these are excluded. Farm mechanization describes the substitution of human labour on the farm whereas agricultural mechanization spans the whole agricultural value chain (Daum and Kirui, 2021; Malabo Montpellier Panel, 2018) (see Figure 1). Agricultural mechanization comprises many types of machinery and implements and should not be equated with the use of tractors. However, tractors are a cornerstone of farm mechanization; they are able to push and pull implements such as ploughs, rippers, planters, sprayers and power stationary machinery such as pumps, shellers and threshers (Valle and Kienzle, 2020). Agricultural mechanization does comprise the use of draught animal traction (such as horses, oxen and donkeys), while agricultural motorization focuses on the use of mechanical power, which can be run with fossil energy as well as renewable energy (FAO and AUC, 2018).

Figure 1. Mechanization along the value chain



Source: Adapted from Daum, T. & Kirui, O. 2021. Mechanization along the value chain. In: *From Potentials to Reality: Transforming Africa's Food Production*. Bern, Peter Lang.

Norman *et al.* (1988) and Pingali (2007) make a strong case for distinguishing between the mechanization of power-intensive (requiring much energy) and control-intensive (requiring careful decision-making) activities (see Table 1). Power-intensive activities are typically mechanized first, while control-intensive activities are mechanized later (Binswanger and Donovan, 1987; Norman *et al.*, 1988; Pingali, 2007). This is because power-intensive activities are associated with a higher labour need and burden and due to the fact that the mechanization of control-intensive activities tends to require more expensive machinery (Binswanger and Donovan, 1987). Table 1 also distinguishes between stationary and mobile operations. Setting up asset-sharing arrangements (e.g. cooperative ownership and service markets) tends to be associated with fewer challenges concerning stationary activities. One can also distinguish between time-bound activities (e.g. planting and harvesting of cereals) and activities that allow more flexibility (e.g. milling) since this affects the ability to share assets.

Table 1. Comparison of agricultural operations

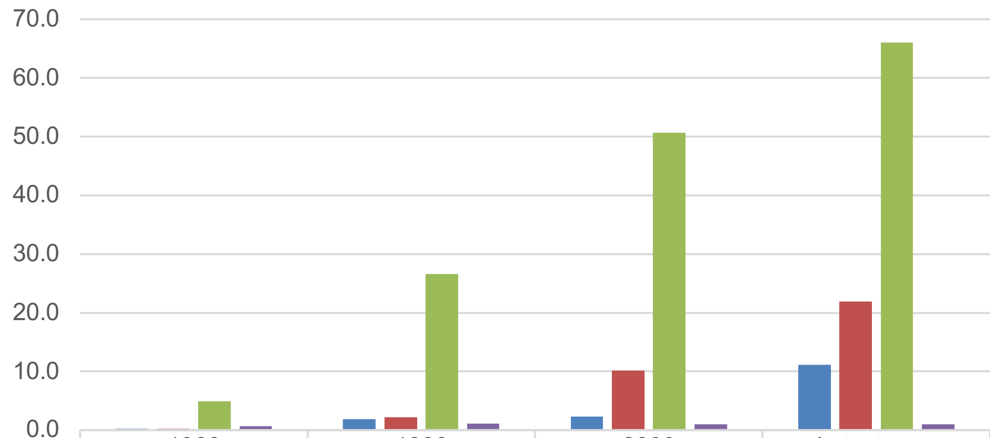
	Power-intensive	Control-intensive
Mobile	Tillage, harvesting cereals, transportation	Planting, weeding, pest control, harvesting, i.e. of specialty crops
Stationary	Pumping, threshing, grinding, milling, wood cutting	Cleaning, winnowing, milking

Source: Adapted from Pingali, P. 2007. Chapter 54 Agricultural Mechanization: Adoption Patterns and Economic Impact. In: *Handbook of Agricultural Economics*. pp. 2779–2805. Vol. 3. Elsevier. https://doi.org/10.1016/S1574-0072(06)03054-4

3 State of mechanization in the Global South

There are large disparities regarding mechanization in the Global South. Latin America and the Caribbean have the highest rates of tractor use across the three developing regions, followed by Asia, which is catching up rapidly, while progress in sub-Saharan Africa has been limited (see Figure 2). As the following sections will show, mechanization trajectories within these world regions can be diverse, as geographical, agroecological and socioeconomic characteristics are heterogeneous. As cross-country data is available, the number of tractors per 1 000 farm workers is often used as a proxy for overall mechanization. However, the underlying data for this is partially patchy and outdated. Moreover, the number of tractors per 1 000 farm workers ignores the role of tractor sizes, service markets, animal traction and other types of equipment. For example, mechanization appears larger in Asian countries when considering service markets, which enable the spread of tractors across many farms. Also, while there are large disparities regarding tractor use, some other types of equipment such as stationary machines (e.g. for milling) have spread more quickly and equitably across the Global South (Pingali, 2007).

Figure 2. Tractors per 1 000 farm workers across world regions



	1960	1980	2000	Latest year
Eastern Asia	0.2	1.9	2.3	11.1
South Asia	0.2	2.2	10.2	21.9
Latin America	4.9	26.6	50.7	66.0
Sub-Saharan Africa	0.7	1.1	1.0	1.0

Note: Latest is mostly 2009 but in some cases much earlier.

Source: Fuglie, K., Gautam, M., Goyal, A. & Maloney, W.F. 2019. *Harvesting prosperity: technology and productivity growth in agriculture*. Washington, DC, World Bank. https://doi.org/10.1596/978-1-4648-1393-1

3.1 Asia

Asia was the least mechanized of all world regions in the 1960s (see also Figure 2). However, while Asian farmers used few tractors, their farming systems were already quite intensive and the use of animal traction was common for land preparation and irrigation (e.g. to drive Persian wheels), which helped facilitate the rapid mechanization in the subsequent decades (Diao, Takeshima and Zhang, 2020; Lawrence and Pearson, 2002). Motorized mechanization accelerated first in response to agricultural intensification as part of the green revolution and later in response to rising rural wages due to structural transformation and urbanization (Diao, Takeshima and Zhang, 2020; Pingali, 2007). Power-intensive activities such as pumping, threshing and milling were already motorized in many areas during the 1950s and 1960s (Pingali, 2007). Increasing labour shortages and rising rural wages have been expanding the use of tractors from mainly power-intensive land preparation to control-intensive planting, pest control, harvesting and processing (Diao, Takeshima and Zhang, 2020).

There are some regional disparities. Some countries witnessed the first waves of tractorization in the 1970s and 1980s (e.g. China, India and Thailand), while others experienced it in the 1990s and the 2000s (e.g. Bangladesh) and the 2010s (e.g. Myanmar). Others have seen more limited progress towards the use of tractors, such as mountainous Nepal (Belton *et al.*, 2021; Diao *et al.*, 2020). Bhattarai *et al.* (2020) estimate that today, land preparation on up to 90 percent of the farmland in India is motorized. In rice production, the share of farmland prepared with machinery is above 85 percent in Bangladesh, China, Myanmar and Sri Lanka (Abeyratne and Takeshima, 2020; Ahmed and Takeshima, 2020; Win, Belton and Zhang, 2020; Zhang, Yang and Reardon, 2017). In contrast, only around 23 percent of the farmers in mountainous Nepal use tractors and power tillers, but 46 percent do so in Nepal's more flat Terai zone (Takeshima and Justice, 2020). Mechanization continues to be more limited regarding harvesting, although combine harvesters are on the rise across various Asian countries (Diao, Takeshima and Zhang, 2020; Yang *et al.*, 2013).

Farm mechanization is increasing despite small farm sizes (often perceived to be a constraint to mechanization) thanks to technological and institutional innovations (Bhattarai *et al.*, 2020; Diao, Takeshima and Zhang, 2020). While larger farmers generally had a head-start regarding mechanization, these innovations facilitated mechanization among smallholder farmers (Diao, Takeshima and Zhang, 2020). Technological innovations include small four-wheel tractors and two-wheel tractors (Diao, Takeshima and Zhang, 2020; Justice and Biggs, 2020). Two-wheel tractors (power tillers) are more common in wetland rice production systems and four-wheel tractors dominate in production drylands and non-rice production systems (Pingali, 2007). Sophisticated market-led service markets have evolved in various Asian countries (Diao, Takeshima and Zhang, 2020; Justice and Biggs, 2020). In Bangladesh, only four percent of farm households own tractors (four-wheeled or two-wheeled) but 89 percent hire them, of which 80 percent own less than 1 ha of land (Diao, Takeshima and Zhang, 2020). In China, migratory service providers are traveling across agroecological zones with fleets of combined harvesters (Yang *et al.*, 2013; Zhang, Yang and Reardon, 2017) and service providers using drones for pest control are on the rise (Iost Filho *et al.*, 2020).

Various Asian countries have built a strong local manufacturing sector, producing locally-adapted and affordable machinery, ranging from small-scale equipment such as two-wheeled tractors (including power tillers), shallow tube wells, pumps, threshers and grain mills to four-wheeled tractors (Belton *et al.*, 2021; Cramb and Thepent, 2020; Justice and Biggs, 2020). India has become the world's largest producer of tractors, with around 600 000 sold yearly (Bhattarai *et al.*, 2020). China is taking a pioneering role in the use of agricultural drones (Diao, Takeshima and Zhang, 2020). Mechanization in Asia countries was mainly driven by private markets (Diao *et al.*, 2014; Diao, Takeshima and Zhang, 2020). Where governments played a larger role, they typically assisted this process by ensuring a conducive business environment, for example, by investing in knowledge and skills development, improving trade and customs policies and regulations, facilitating access to finance, organizing land reforms, setting up public irrigation systems and investing in rural infrastructure (Cramb and Thepent, 2020; Diao, Takeshima and Zhang, 2020).

3.2 Africa

African agrifood systems are the least mechanized of all world regions (Daum and Birner, 2020). Around 10 percent of crop farmers are estimated to use tractors (FAO and AUC, 2018), which is usually the first farming step to become mechanized (Binswanger, 1986). There were many efforts to promote mechanization in newly independent African countries in the 1960s and 1970s by providing subsidized machinery to farmers, running state and block farms, and setting up public hire centres, often with support from donors (FAO and AUC, 2018; Pingali, 2007). Such efforts have proven costly and mostly failed due to governance challenges such as lack of investment into knowledge and skills development, low access to fuel and spare parts, and rent-seeking and corruption (FAO and AUC, 2018; Pingali, 2007). Another reason is that such efforts artificially pushed farm mechanization despite a lack of real demand for mechanization due to a lack of farming system evolution and structural transformation (Diao, Takeshima and Zhang, 2020; Norman *et al.*, 1988; Pingali, 2007).

Farming systems are now evolving and rural wages are rising in some areas, leading to mechanization in selected pockets (Daum and Birner, 2020; Diao, Takeshima and Zhang, 2020; FAO and AUC, 2018). Tractors are in particular concentrated in Northern Africa and South Africa (Mrema, Baker and Kahan, 2008). Kirui (2019) estimated the share of tractor use to be as high as 57 percent in Egypt and 70 percent in South Africa. Some sub-Saharan African countries have also seen progress towards mechanization. In Ghana, up to one-third of farm households use tractors for land preparation, although uptake varies greatly at the regional level, with mechanization levels being as low as 2 percent in parts of the forest zone and as high as 88 percent in the savannah zones (Diao, Takeshima and Zhang, 2020). In the United Republic of Tanzania, up to 14 percent of the farmland is cultivated with tractors, with mechanization levels being highest in large-scale commercial farming areas (Mrema, Kahan and Agyei-Holmes, 2020). In Nigeria, 7 percent of farmers use tractors (Takeshima and Lawal, 2020). In most other African countries, tractor use is very low (Mrema, Baker and Kahan, 2008). Kirui (2019) estimated the share of tractor use among farmers to be below 1 percent in Cameroon, Niger and Senegal. In Ethiopia, around 1 percent of farm plots are cultivated with tractors, mainly in easy-to-mechanize wheat-barley systems, which are also dominated by large farms and have witnessed the emergence of service markets for wheat combining (Berhane *et al.*, 2020).

While African farming systems are characterized by limited mechanization in the form of tractors and power tillers, animal traction is widespread in some countries and some stationary activities are typically mechanized. In Ethiopia, up to 80 percent of farmers use animal traction for land preparation (Berhane *et al.*, 2020). In Nigeria and the United Republic of Tanzania, this share stands at around 25 percent (Mrema, Kahan and Agyei-Holmes, 2020; Takeshima and Lawal, 2020). On average, 15 percent of farmers are estimated to use animals for land preparation in Africa (FAO and AUC, 2018). While tractor use has remained limited, Pingali (2007) provides historical accounts showing that some stationary activities have been mechanized for a long time, for example, mechanical mills for power-intensive milling are popular for many decades.

Diao *et al.* (2020) suggest that African agricultural mechanization is no longer held back by a lack of demand but rather by supply-side constraints (e.g. lack of knowledge and skills, trade regulations, custom policies and poor infrastructure, among others). It is thus problematic that many governments do not focus on addressing such supply-side constraints by creating a conducive environment for market-led mechanization. Instead, government focus more on efforts to directly promote mechanization (e.g. by pursuing large-scale programmes to import machinery and distribute it a highly subsidized rates to farmers, by setting up public mechanization hire schemes and planning national tractor assembly plants) (Daum and Birner, 2020). This may be partially due to political economy problems such as desire to create media attention and enable rent-seeking, clientelism and political targeting (Benin, 2015; Cabral, 2019; Daum and Birner, 2017; Diao *et al.*, 2014). Such efforts are high on the agenda in countries such as Benin, Burkina Faso, Ghana, Kenya, Mali, Mozambique, Nigeria and Zimbabwe, among many others and again show signs of failure (Daum and Birner, 2017, 2020; Diao *et al.*, 2014).

There is now a growth of private-sector channels supplying both used and new machinery, and including efforts from global machinery manufacturers (e.g. AGCO, John Deere and Mahindra), as well as smaller companies from the Global South (Daum and Birner, 2020). Across Africa, local manufacturing sectors are emerging for simple types of equipment. Private mechanization service markets are also emerging in several countries (Berhane *et al.*, 2020; Daum and Birner, 2020; Diao *et al.*, 2014). All of these supply-side dynamics contribute to falling machinery costs, which were historically higher in Africa than elsewhere.

3.3 Latin America and the Caribbean

Latin America and the Caribbean has the highest levels of farm mechanization of the three world regions covered in the paper, although most countries fall behind the degree of mechanization witnessed in high- and upper-middle-income countries (Elverdin, Piñeiro and Robles, 2018). In the 1960s, there were five tractors per 1 000 farm workers. In the 2010s, this share increased to around 65 tractors (see Figure 2). This represents, on average, a 4 percent increase in the number of tractors annually between 1950 and 2008, with the most rapid growth during the 1950s and 1960s (Martín-Retortillo *et al.*, 2019). In the last few decades, annual growth rates have fallen, suggesting a saturation and reflecting a shift towards fewer but larger tractors in some countries (Martín-Retortillo *et al.*, 2019). Similar to other world regions, these continent-wide numbers mask large heterogeneity between countries. The share of tractors per 1 000 farm workers is highest in Argentina and Uruguay – followed by Brazil, the Bolivarian Republic of Venezuela, Chile, Panama and Mexico (Elverdin, Piñeiro and Robles, 2018; Martín-Retortillo *et al.*, 2019). The country that witnessed the most rapid mechanization progress was Brazil, with an annual growth rate of 7 percent (Martín-Retortillo *et al.*, 2019). In contrast, countries such as the Plurinational State of Bolivia, El Salvador, Peru and Colombia, among others, all started at a low level and witnessed limited progress concerning tractorization (Elverdin, Piñeiro and Robles, 2018; Martín-Retortillo *et al.*, 2019). Pingali (2007) has noted a rise of large-scale processing plants across Latin America and the Caribbean, replacing smaller village-based plants. In general, Latin American and Caribbean countries are characterized by the coexistence of large-scale, highly mechanized farms and smallholder farms in remote and hilly areas, which are often not as mechanized (Antle and Ray, 2020; ECLAC, FAO and IICA, 2017; Elverdin, Piñeiro and Robles, 2018; da Silva *et al.*, 2018).

Although mechanization in Latin America and the Caribbean was largely driven by private actors, governments have played a key role in creating an enabling environment for mechanization. Examples include public programmes to facilitate access to credit at low-interest rates and tax exemptions in various countries such as Argentina, Costa Rica, Ecuador and Peru (ECLAC, FAO and IICA, 2017; Elverdin, Piñeiro and Robles, 2018). Moreover, several countries have exempted agricultural machinery from imported duties, for example Peru (ECLAC, FAO and IICA, 2017). However, in countries where mechanization levels are more limited, there appears to be a lack of public sector support to create an enabling environment concerning knowledge and skills development, access to finance and rural infrastructure, among others (Elverdin, Piñeiro and Robles, 2018). In Brazil and Mexico – and to some degree Argentina – strong agricultural machinery manufacturing sectors that sell to both regional and global markets have emerged, including large machinery such as tractors and harvesters (Elverdin, Piñeiro and Robles, 2018). In some countries, such as Argentina, agricultural mechanization service markets play a great role for smallholders to access mechanization (Elverdin, Piñeiro and Robles, 2018).

4 Drivers

Mechanization patterns are affected by drivers and barriers affecting demand and supply. Drivers include changing land and labour endowments and farming system evolution (see Section 4.1), and structural transformation, rising wages and market developments (see Section 4.2). Potential barriers relate to technology costs, small and fragmented fields, geographic and agroecological conditions (see Section 4.3), and a lack of enabling environments (and Section 4.4).

4.1 Land and labour endowments and farming system evolution

Different theories help to explain agricultural mechanization patterns. A prominent theory is that of induced agricultural innovation, which focuses on land and labour endowments (Hayami and Ruttan, 1970; Ruttan, 1977) as well as the theory of farming system evolution (Boserup, 1965; Ruthenberg, 1980). While each of these theories has its limitations, taken together they constitute a powerful analytical toolbox for explaining mechanization trajectories (Diao, Takeshima and Zhang, 2020). The theory of induced agricultural innovations suggests that innovations are driven by the relative endowments and prices of production factors such as land and labour (Hayami and Ruttan, 1970). Private actors develop and adopt technologies that "facilitate the substitution of relatively abundant and hence cheap factors for relatively scarce and hence expensive factors of production" (Ruttan, 1977). Public sectors can facilitate this process via agricultural research and development and land reforms, among others, as formulated in the theory of induced institutional innovation (Ruttan and Hayami, 1984). In labour-scarce areas, farmers first adopt labour-saving technologies (e.g. mechanization and herbicides). In land-scarce areas, farmers first adopt land-saving technologies (e.g. improved seeds, fertilizer and irrigation, which facilitates multiple cropping and higher yields). This theory explains the earlier adoption of land-saving technologies in highly populated Asia as compared to Africa and the high degree of mechanization in Latin America and the Caribbean countries with larger farm sizes. However, it fails to explain the high degree of mechanization in labour-abundant, land-scarce Asia as compared to historically labour-scarce, land-abundant Africa (Diao, Takeshima and Zhang, 2020; Elverdin, Piñeiro and Robles, 2018; Pingali, 2007). This is predominantly because the theory of induced agricultural innovation neglects the role of farming system evolution and structural transformation.

The theory of farming system evolution has been developed by Boserup (1965) and Ruthenberg (1980) and adopted for mechanization by Norman *et al.* (1988). In land-abundant, labour-scarce areas, the rational choice of farmers is not to mechanize but to practice extensive shifting cultivation, leaving forest and bush fallow for long periods, which has low labour requirements (Boserup, 1965; Diao, Takeshima and Zhang, 2020; Ruthenberg, 1980; van Vliet *et al.*, 2012). This can be different in areas with low population densities but strong market demand where farmers have an incentive to produce surplus food (Nin-Pratt and McBride, 2014). Increasing population densities cause a transition towards annual and multiple cropping (Boserup, 1965; Ruthenberg, 1980). This intensification is associated with higher labour requirements and triggers the mechanization of the most labour-intensive farming steps even where rural wages are still low (Diao, Takeshima and Zhang, 2020; Norman *et al.*, 1988). Farmers tend to first mechanize using animal traction and later use tractors when animal traction becomes exceedingly expensive due to pressure to convert livestock grazing land to cropland (Norman *et al.*, 1988; Ruthenberg, 1980).

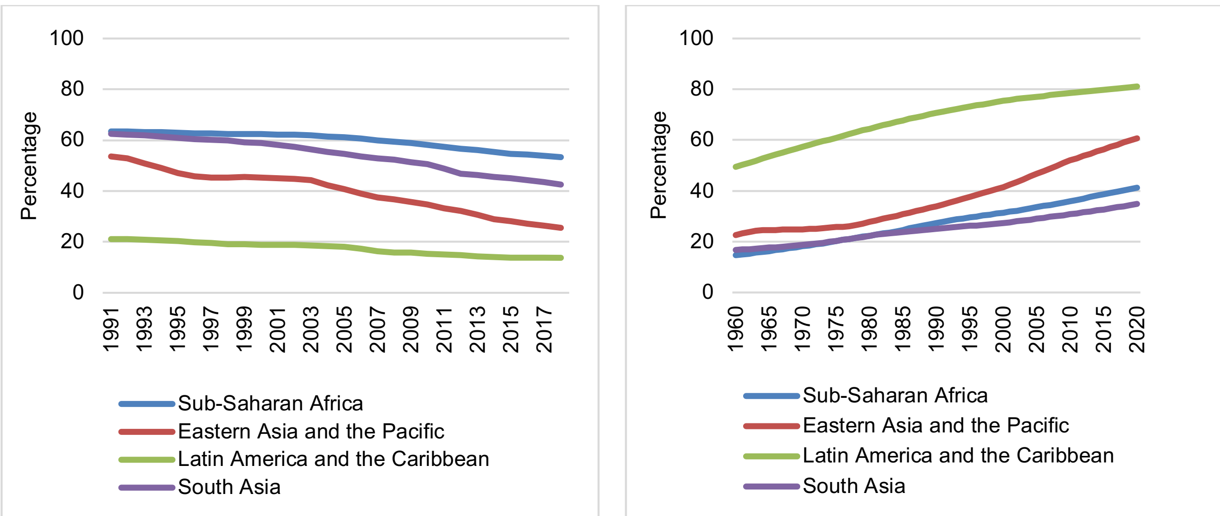
Farming system evolution helps to explain continental differences. Densely populated Asian countries witnessed high levels of farming system evolution in the 1960s, which served as a key basis for the rapid mechanization in the following decades, a trend that was further pushed due to intensification as part of the green revolution (Diao, Takeshima and Zhang, 2020; Pingali, 2007). In Africa, shifting cultivation was still widespread in the 1970s (Heinimann *et al.*, 2017) and farmers faced few market incentives to intensify and mechanize (Diao, Takeshima and Zhang, 2020; Pingali, 2007). Mechanization was only widespread on large commercial farms, partly as a legacy of colonization, and partly as component of state-supported block farm and tractor hire schemes, many of which soon collapsed (Norman *et al.*, 1988; Pingali, 2007). In the last few decades, shifting cultivation has declined and cropping intensities have increased in all but a few countries (Binswanger-Mkhize and Savastano, 2017; Diao, Takeshima and Zhang, 2020; Heinimann *et al.*, 2017; Sebastian, 2014; van Vliet *et al.*, 2012). The shift towards permanent cropping is slowly increasing the demand for mechanization, although farming system evolution is only "a necessary but not sufficient condition" for mechanization (Diao *et al.*, 2014).

4.2 Structural transformation, rural wages and market developments

Mechanization patterns are also explained by structural transformation, rural wages and market developments. During structural transformation, better-paying industries and service sectors pull labour out of agriculture, leading to labour shortages, rising wages and opportunity costs (Diao *et al.*, 2014; Diao, Takeshima and Zhang, 2020). Structural transformation is typically associated both with a falling share of employment in agriculture and with urbanization (see Figure 3), as industries and service sectors are more likely to be located in urban areas.

Figure 3. Structural transformation in agricultural employment and urbanization

a. Share of employment in agriculture **b. Share of urban population**



Source: World Bank. 2022. World Bank Open Data. In: *World Bank*. https://data.worldbank.org

Many Asian countries witnessed structural transformation, urbanization and rapidly rising rural wages in the last decades. For example, real rural wages tripled between 1992 and 2008 in Vietnam (Takeshima and Justice, 2020) and rose by 42 percent between 2011 and 2016 in Myanmar (Win, Belton and Zhang, 2020). In China, farm wages grew between 8 and 10 percent annually from 1997 to 2016, leading to a sharp rise in mechanization and a halving of the labour days per hectare (Wang *et al.*, 2016). In Nepal, the wage of rural labourers for ploughing rose by 86 percent for men and 195 percent for women between 1995 and 2010 (Takeshima and Justice, 2020). While farming system evolution drives the mechanization of power-intensive farming steps even where wages are low, structural transformation and rising rural wages tend to drive the mechanization of control-intensive farming steps (Binswanger, 1986; Norman *et al.*, 1988; Pingali, 2007). In many Asian countries, this is now leading to full mechanization, as exemplified by the rise of combined harvesters (Diao, Takeshima and Zhang, 2020).

In Africa, labour is moving out of agriculture more slowly and urbanization rates are increasing less quickly than in other world regions (see Figure 3). However, there are also growing rural labour constraints in several countries (Diao, Takeshima and Zhang, 2020). In Ethiopia, structural transformation has caused a rise in the real wages of unskilled labourers in rural areas by more than 50 percent in the last two decades (Berhane *et al.*, 2020). In Ghana, new opportunities in the non-farm sectors have led to rising rural wages, causing labour to account for 45 percent of the overall input costs of farmers (Diao *et al.*, 2014). In Africa, relatively limited structural transformation means that, on average, mechanization progress has been slow and focused on the most power-intensive activities such as land preparation, transportation and processing (Daum and Birner, 2020; Diao, Takeshima and Zhang, 2020). Importantly, labour availability for agriculture can also be affected by the rising share of children going to school or by health problems and death (e.g. from the human immunodeficiency virus [HIV]), among others (Bishop-Sambrook, 2005; Jayne, Mather and Mghenyi, 2010).

Farmers face incentives to intensify and then mechanize where there is a market for their produce. Across the world, population growth and rising prosperity are leading to growing food demand. Moreover, rising urban prosperity is leading to changing food demand patterns. For example, demand is increasing for easy-to-cook cereals, such as wheat and maize, which are more labour-intensive but easier to mechanize than roots and tubers, as well as towards vegetables, fruits and livestock products, which are more labour-intensive than staple crops (Diao, Takeshima and Zhang, 2020; Tschirley *et al.*, 2015). All of this incentivizes farmers to intensify production and generates the incentives and purchasing power needed to adopt labour-saving mechanization. This can be observed in many Asian countries (Diao, Takeshima and Zhang, 2020). In many African countries, farmers do not experience the same opportunities as they are disconnected from urban markets due to a lack of market infrastructure and high transaction costs (de Brauw and Bulte, 2021; Diao, Takeshima and Zhang, 2020; Jayne, Mather and Mghenyi, 2010). For example, in Nigeria, rising food demand has been met mainly through food importation, and thus agricultural mechanization has stalled despite structural transformation (Takeshima and Lawal, 2020).

4.3 Technology costs, farm sizes and agroecological conditions

Mechanization patterns are also shaped by endogenous factors such as technology costs, and indeed, falling technology costs have greatly contributed to mechanization in Asia (Diao, Takeshima and Zhang, 2020). In Africa, machinery was historically imported from Europe and Northern America, where technology costs were high. Technology costs are now falling with growing competition from manufacturers from Asia (i.e. China India) and South America (i.e. Brazil) who offer cheaper and smaller-sized machinery (FAO and AUC, 2018). But technology costs (machinery, spare parts) are still higher as compared to Asia, partially due to disadvantageous import policies (FAO and AUC, 2018). Poor infrastructure and high transaction costs can also raise the prices for mechanization services (e.g. for land preparation). In many

African countries, mechanization services are expensive, costing as much as the equivalent of 500 kg of maize (FAO and AUC, 2018).

Many agricultural innovations are first adopted by large farms with better tenure security, access to credits, extension, markets and the ability to take risks, among others (Feder, Just and Zilberman, 1985). In the case of mechanization, large farms have further adoption advantages because unlike other agricultural innovations such as seeds and fertilizer, mechanization technologies are indivisible and associated with economics of scale, putting farmers who operate on small and fragmented plots at a disadvantage (Antle and Ray, 2020). It is therefore not surprising that there is both historic (Binswanger and Donovan, 1987) and contemporary (Berhane *et al.*, 2020; Elverdin, Piñeiro and Robles, 2018; Takeshima, 2017) evidence from across low- and lower-middle-income countries that large farms often mechanize earlier than small farms. The same is true in many high- and upper-middle-income countries. However, small farm sizes are not necessarily at a disadvantage where technological and institutional solutions for smallholder mechanization evolve. In Asia, mechanization rates are high despite small farm sizes thanks to smaller-sized machinery and strong service markets (Bhattarai *et al.*, 2020; Cramb and Thepent, 2020; Diao, Takeshima and Zhang, 2020). Such mechanization service markets are on the rise across various African countries (Adu-Baffour, Daum and Birner, 2019; Berhane *et al.*, 2020; Cabral and Amanor, 2022; Diao *et al.*, 2014; Jayne *et al.*, 2019; Takeshima and Lawal, 2020; Van Loon *et al.*, 2020). In Africa, service markets are partly driven by a rise of medium-scale farmers (Jayne *et al.*, 2019) who can afford to buy machinery but still have to provide services to other farmers to ensure high utilization rates.

Geographic and agroecological factors can also shape mechanization patterns. Mechanization is easier on flat terrains, as sloped and hilly land makes machinery more difficult to operate and creates a risk of overturning. In Nepal, mechanization levels are almost twice as high in the flat Terai zone as compared to mountainous areas. In Ethiopia, mechanization levels are also higher in the flat lowlands (Berhane *et al.*, 2020). Mechanization service markets are more difficult to set up in semi-arid areas with short farming seasons (Diao *et al.*, 2014). Mechanization can also be influenced by soil types and soil workability constraints (Diao, Takeshima and Zhang, 2020). For example, soils with greater bulk densities tend to require more farm power (Binswanger and Donovan, 1987). The high prevalence of trees or stumps can also prevent mechanization (Daum and Birner, 2017). Lastly, crop types matter. In Latin America and the Caribbean and in Asia, easy-to-mechanize cereal crops, such as wheat and maize, dominate agricultural production (FAO and AUC, 2018). In Africa, mechanization levels are higher in the cereal-based farming systems of eastern and southern Africa (FAO and AUC, 2018). Roots and tubers, which are widespread in western and central Africa, have received much less attention from global machinery manufacturers, partly due to different mechanization needs and partly due to limited market size. Tree-based cropping systems are also difficult to mechanize (Cramb and Thepent, 2020; Norman *et al.*, 1988). The demand and scope for irrigation technologies depend on rainfall patterns and water availability. In some world regions, in particular in central Africa, animal traction never evolved due to a high prevalence of animal disease (Alsan, 2015; Mrema, Kahan and Agyei-Holmes, 2020; Norman *et al.*, 1988).

4.4 Enabling environments

Agricultural mechanization technologies are embodied private goods and, as such, private markets have a strong incentive to provide mechanization opportunities where there is demand (Sunding and Zilberman, 2001). Mechanization has been driven by private markets in

Latin America and the Caribbean and in Asia (see Section 3). In Africa, private markets are also emerging in some countries; however, many governments aim to bypass markets and pursue public mechanization programmes (Daum and Birner, 2020; Diao, Takeshima and Zhang, 2020). Such efforts have been typically short-lived due to lack of economic demand, governance challenges and struggles to come up with a self-sustaining system for the supply of tractors, spare parts and repairs (Daum and Birner, 2017; FAO and AUC, 2018; Norman *et al.*, 1988; Pingali, 2007). Public programmes are likely to fail where private markets are missing due to lack of demand and can prevent the emergence or crowd out private actors (Daum and Birner, 2020; Pingali, 2007). Public supply-side pushes where farmers would not otherwise intensify and mechanize can also have large negative effects on employment and equity (Pingali, 2007).

However, governments can have a key role in supporting markets, particularly when such markets are undermined by market failures (Daum and Birner, 2017; Diao, Takeshima and Zhang, 2020). Governments played a key role in supporting private sector mechanization in Northern America and Europe (Daum, Huffman and Birner, 2018) and Asia (Belton et al., 2021; Diao *et al.*, 2014; Diao, Takeshima and Zhang, 2020). Diao *et al.* (2020) have argued that mechanization progress has been more rapid in Asia as compared to Africa as governments have avoided supply-side constraints to mechanization, which can be caused by insubstantial or improper government action, such as state-led programmes crowding out private investments. The theory of induced institutional change (Ruttan and Hayami, 1984) predicts "that the tension caused by the increasing scarcity of resources stimulates technological change to save those resources as well as new institutions that support such technological change" (Otsuka and Place, 2013). The importance of the enabling environment is discussed in more detail in Section 7.1.

5 Opportunities and risks for sustainable agrifood system transformation

Agrifood system innovations are typically associated with a complex set of synergies and trade-offs across the three pillars of sustainability (Antle and Ray, 2020). Agricultural mechanization is no exception and comes with both opportunities and risks for sustainable agrifood system transformation, including regarding economic (see Section 5.1), environmental (see Section 5.2) and social (see Section 5.3) aspects. As will be shown, and as remarked by Ströh de Martínez *et al.* (2016), mechanization per se is a neutral process and its effects depend highly on the context and accompanying practices and policies and investments.

5.1 Economic dimension

Labour productivity, labour use and employment

Substituting human power with animal power or mechanical power can greatly enhance agricultural labour productivity (Binswanger, 1986; Diao, Takeshima and Zhang, 2020; Hayami and Ruttan, 1970; Sims and Kienzle, 2006). Labour productivity describes the output per unit of labour input. Mechanization affects the labour inputs but can also affect outputs. Changes in land and labour productivity across the world during the past decades reveal strong similarities between agricultural labour productivities and the mechanization patterns described in Section 3 (Fuglie *et al.*, 2019).

In a review on labour use effects of tractors, Norman *et al.* (1988) reported 22 of 24 studies to have found a reduction in labour once tractors were used rather than draught animals, with 12 studies reporting labour reductions above 50 percent. Sims and Kienzle (2016) show that primary tillage using manual tools requires around 500 labour hours per hectare as compared to only 60 hours using animal traction and 1–2 hours using tractors. In a recent study in Ethiopia, tractor-using households used less than half the labour per hectare as non-tractor-using households (Berhane *et al.*, 2020). In a study in Zambia, farm families with mechanized land preparation used 645 labour hours per ha of maize production per season compared to 1 133 among non-mechanized households, benefiting men, women and children (Adu-Baffour, Daum and Birner, 2019). Such households achieved twice the gross margin per hour of farm labour (Adu-Baffour, Daum and Birner, 2019). Processing, preserving, storage and transportation technologies can equally raise labour productivity (Daum and Kirui, 2021). However, while mechanization raises labour productivity, the overall labour input can decline, stagnate, or increase. In the Zambian study above, labour input per hectare declined but the overall labour input per farm declined only marginally since the household achieved higher yields and expanded farmland, both of which increased labour demand during subsequent farming steps. Similarly, in a study in Côte d'Ivoire, tractor use for land preparation induced the application of modern inputs and better crop management, increasing land and labour productivity as well as the overall labour input per hectare (Mano, Takahashi and Otsuka, 2020).

There are concerns that mechanization leads to unemployment, in particular in countries that are perceived to have surplus labour (Binswanger and Donovan, 1987; Daum and Birner, 2020; Pingali, 2007). Given the importance of decent employment opportunities for sustainable development, as exemplified by SDG 8, such concerns should be taken seriously. Theoretical and empirical evidence suggests that unemployment effects are complex depending on the farm steps being mechanized, second-round effects due to change in yields and farmland expansion, the former source of labour and non-farm employment opportunities, among others (Binswanger, 1986; Daum and Birner, 2020; Pingali, 2007). In many scenarios, mechanization has no or even positive effects on employment; however, negative effects can be observed where mechanization is pushed in areas without labour shortages, rising wages and alternative employment opportunities (Binswanger, 1986; Pingali, 2007). In the following points, some typical scenarios are illustrated:

- **Increasing labour input, increasing employment:** Mechanization is labour saving in the sense that it reduces labour input per unit of output, but it can lead to an overall increase in labour input due to second-round effects. Mechanization is often adopted in a sequential process, starting with the most pronounced labour bottlenecks and power-intensive operations such as land preparation. Labour input may then increase for not yet mechanized activities such as weeding and harvesting as farmers expand the area under cultivation or intensify and raise yields (Binswanger, 1986; Pingali, 2007). In India, Rajkhowa and Kubik (2021) found that the use of tractors and draft animals increased hired labour use by 12 percent due to area expansion and higher input use. Similar second-round effects have been observed in Botswana (Panin, 1995), Ghana (Benin, 2015; Kirui, 2019; Cossar, 2019), Niger and Zimbabwe (Kirui, 2019), and Zambia (Adu-Baffour, Daum and Birner, 2019). Such effects can also be associated with the mechanization of other farming steps. For example, pumps for irrigation increase cropping intensities and yields, often raising the demand for labour (Binswanger, 1986; Pingali, 2007).
- **Declining labour input, no unemployment:** Even where mechanization leads to an overall reduction in labour inputs, this does not necessarily cause unemployment. Mechanization does not cause unemployment when it is a response to structural transformation, during which people leave farming roles to seek more attractive alternative employment opportunities (Binswanger, 1986; Pingali, 2007). There are also no unemployment effects where mechanization replaces unpaid family work, including from women and children (Adu-Baffour, Daum and Birner, 2019; Daum and Birner, 2020; Pingali, 2007). In a case study in Zambia, mechanization reduced family labour and increased hired labour (Adu-Baffour, Daum and Birner, 2019).
- **Declining labour input, rising unemployment:** However, there are also cases where mechanization can lead to unemployment. This can be the case where markets are distorted, for example, when mechanization is artificially pushed by large subsidies (Binswanger, 1986; Pingali, 2007). Pingali (2007) has shown that this was the case where the mechanization of control-intensive operations (e.g. weeding, harvesting) was promoted in areas where rural wages were low and labour markets existed for such activities.

Mechanization can also lead to second-round effects on employment beyond the specific farm. For example, farm mechanization may affect employment opportunities down the value chain where it affects overall production volumes (through effects on yields and farmland area). In addition, there can be spillover effects from prospering farmers to the wider rural and urban economy via many forward and backward linkages.

Yields, crop loss and food safety

Agricultural mechanization is sometimes viewed as a technology to “save” labour, with limited effects on land productivity (Binswanger, 1986). While this is true in some cases, in other cases mechanization can help to safeguard or raise yields. Where land is available and cheap, using tractors to cultivate more land rather than trying to raise yields can be the rational choice of farmers (Baudron *et al.*, 2012; Bishop-Sambrook, 2005; Nin-Pratt and McBride, 2014). This has been observed in parts of Ethiopia (Berhane *et al.*, 2020) and Ghana (Houssou and Chapoto, 2014). Evidence also suggests that replacing draught animals with tractors has limited yield effects (Bhattarai *et al.*, 2020; Pingali, 2007). However, mechanization can raise land productivity where it addresses labour bottlenecks and shortages, can increase cropping frequencies, trigger the adoption of yield-increasing technologies and reduce crop losses, as explained below:

- **Addressing labour bottlenecks and shortages:** While, in theory, high yields are possible without mechanization where farm labour is skilled, motivated and abundant at all times, this is often not the case in the real world. There is growing evidence regarding how labour bottlenecks and shortages undermine timely and careful seedbed preparation and crop management and hence yields. Seasonal labour bottlenecks and shortages have always been a feature of rainfed agriculture in arid and semi-humid areas where timing can heavily impact yields (Ruthenberg, 1980). Baudron *et al.* (2015) show that delaying planting reduces yields by up to 1 percent per day. In Ethiopia, labour constraints are responsible for up to 50 percent of yield gaps (Silva *et al.*, 2019). Baudron, Nazare and Matangi *et al.* (2019) found that a lack of farm power is a key factor explaining yield gaps in Eastern and Southern Africa. In Zambia, mechanized land preparation helped farmers to increase yields by 25 percent (Adu-Baffour, Daum and Birner, 2019). A study across eleven African countries found that tractor use increases maize yields by around 0.5 tonnes per ha (Kirui, 2019).
- **Increasing cropping frequencies and adoption of yield-increasing technologies:** In many parts of the world, mechanization in the form of tractors and pumps for irrigation has helped farmers to significantly increase cropping intensity (Diao, Takeshima and Zhang, 2020; Hazell, 1985; Pingali, 2007; Singh, 2001; Tetlay, Byerlee and Ahmad, 1990; Verma, 2006). Mechanization can also affect the adoption of yield-increasing but labour-intensive technologies such as improved seeds and fertilizer (Bhattarai *et al.*, 2020; Diao, Takeshima and Zhang, 2020; Nin-Pratt and McBride, 2014). In a study in China, mechanization led farmers to increase agrochemical use (of which expenses rose by 56 percent) and, consequently, maize yields by 15 percent (Ma, Renwick and Grafton, 2018). In Nigeria, tractors raised the share of farmers using chemical fertilizer by 14 percentage points (Takeshima and Lawal, 2020). In Côte d'Ivoire, tractors induced better agronomic practices and higher input use, increasing yields by 40 percent (Mano, Takahashi and Otsuka, 2020). Farmers adopt some forms of mechanization primarily to safeguard or raise yields. Irrigation can increase or stabilize yields where rains are unpredictable and droughts are common, creating climate resilience (Malabo Montpellier Panel, 2018; Pingali, 2007). In Africa, small- and large-scale irrigation can raise agricultural production by 50 percent (You *et al.*, 2011). Modern precision irrigation technologies can increase both yields and water use efficiency (Malabo Montpellier Panel, 2018; Parthasarathi *et al.*, 2018; Zhang *et al.*, 2021).
- **Reducing crop damages and losses:** In some cases, mechanization can reduce crop damages and losses, effectively increasing the output per unit of land (Daum and Kirui, 2021; Elverdin, Piñeiro and Robles, 2018). A study in Kenya found that 95 percent of potato damage and losses were attributed to lacking harvesting technology (Breuer, Brenneis and Fortenbacher, 2015). In India, Bhattarai *et al.* (2020) found that combined harvesters for harvesting and threshing reduced crop damage and loss of rice and therefore raised yields by 24 percent. In Ethiopia, combined harvesters increase yields by around 20 percent as

harvesting and threshing are otherwise constrained by a lack of labour and the use of rudimentary tools (Berhane *et al.*, 2020).

Mechanization can also help to reduce post-harvest food losses and contribute to food safety. Preservation and storage technologies (e.g. dryers, cold storage) can considerably reduce food losses and enhance food safety, for example by reducing contamination with fungi such as aflatoxins (Salvatierra-Rojas *et al.*, 2017). Processing technologies can also reduce food losses (Elverdin, Piñeiro and Robles, 2018). In Africa, a lack of processing technologies has been estimated to cause an annual loss of 1 million tonnes of rice (Malabo Montpellier Panel, 2018). Transportation technologies (e.g. trucks, cars, motorbikes) can also reduce food losses. Technologies for preservation, storage, processing and transportation are particularly key to reducing food losses regarding nutritious but delicate and perishable food such as fish, fruits, vegetables, meat and dairy products (Daum and Kirui, 2021). In dairy production, a lack of cooling technologies causes milk loss of around 20–30 percent (Salvatierra-Rojas *et al.*, 2017). A lack of technologies to reduce post-harvest losses can also affect agricultural production indirectly by discouraging farmers to produce surplus food for markets in the first place (Daum and Kirui, 2021).

Farmland expansion

Using manual labour constrains how much land farm households can cultivate and how much produce they can handle (Sims and Kienzle, 2016). Mechanization can help households to overcome labour bottlenecks and shortages and expand the area under cultivation where extra land is available and affordable, as is the case in several land-abundant regions across the Global South. In Nigeria, Takeshima and Lawal (2020) found that tractors enabled farmers to expand area cultivation by 0.4 ha. In Ghana, Houssou and Chapoto (2014) found that each additional hectare ploughed using tractors or draft animals is associated with an increase in land cultivated of 14 percent and 13 percent respectively. Also in Ghana, Kansanga *et al.* (2018) found that mechanization allowed smallholder farmers to double farm sizes within ten years (from around 1 to 2 hectares). In eleven African countries, Kirui (2019) found that mechanization significantly increases the amount of cropland cultivated. Mechanization has also affected land expansion in Indonesia (Yamauchi, 2016) and Brazil (de Oliveira *et al.*, 2017), among others. For the respective households, farmland expansion is beneficial. In Zambia, tractor-using households cultivated double the amount of land and achieved twice the income as compared to non-mechanized farmers (Adu-Baffour, Daum and Birner, 2019). Depending on the source of the extra land, farmland expansion effects can be associated with large equity and environmental trade-offs (see Sections 5.2 and 5.3). Farmland expansion effects are more limited where pristine land is not available or well protected and where the land rights of smallholder farmers are well established. Some forms of mechanization reduce farmland requirements as they increase land productivity and reduce food loss.

Income effects and spillovers to wider economy work

Farm households typically aim to maximize real net incomes, among other goals. Mechanization can help farmers to increase labour productivity, a key determinant of incomes (Binswanger, 1986; Diao, Takeshima and Zhang, 2020; Fuglie *et al.*, 2019; Hayami and Ruttan, 1970). Mechanization can affect labour productivity if it enables yield growth, area expansion and value addition, and/or if it decreases labour inputs and costs. In a study in Zambia, mechanized households obtained twice the incomes as compared to non-mechanized farmers after controlling for covariates (Adu-Baffour, Daum and Birner, 2019). In a study in Nigeria, tractor use raises real incomes by 13 percent (Takeshima and Lawal, 2020). Rising agricultural labour productivity can enable households to allocate time away from agriculture and pursue off-farm work (Daum, Capezzone and Birner, 2021; Kansanga *et al.*, 2020; Ma, Renwick and Grafton, 2018; Theis *et al.*, 2019). Pingali (2007) argues that "poor households benefit the most since the released labour can be reallocated for other income-earning activities or leisure" (p. 2800). However, since the overall labour input may stagnate or even rise with mechanization, it does not always enable the pursuance of off-farm activities. Where mechanization raises the overall labour input, this can enhance the income-earning opportunities for hired labourers (Adu-Baffour, Daum and Birner, 2019). Rising farm incomes can lead to spill-over effects from the now more prosperous farmers to the wider rural and urban economy via many forward and backward linkages, including through the consumption of non-farm goods and services (Christiaensen, Demery and Kuhl, 2011; Haggblade, Hazell and Reardon, 2010). Such agricultural transformation processes can reinforce "synergies between farm, down-stream food system and nonfarm activities, where rising incomes in each sector provides a growing market for each other" (Jayne *et al.*, 2019).

Risks and resilience

Mechanization can increase the resilience of farm households to some type of risks; however, it can also create new vulnerabilities. Mechanization can increase resilience to health shocks affecting household labour or hired labour. The ill health or death of labour can greatly undermine the availability of farm power and severely disrupt agricultural production, with effects on food security and poverty, in particular in already poor households (Jayne, Mather and Mghenyi, 2010). Irrigation technologies increase the resilience to climatic shocks, which will become more frequent and severe with climate change. Mechanization can also help increase climate resilience as it allows farmers to complete farming activities more quickly and hence enhances their ability to adapt activities to changing weather patterns (Elverdin, Piñeiro and Robles, 2018). Preservation, processing and storage technologies increase the resilience to food supply and demand disruptions (Huss *et al.*, 2021) and the contamination of harvested food (Salvatierra-Rojas *et al.*, 2017). Where mechanization leads to higher incomes, this increases the resilience to all types of shocks.

However, mechanization may also create new vulnerabilities. The reliance on machines makes farmers vulnerable to breakdowns, which can have severe effects when happening during time-bound activities (Daum and Birner, 2017). Farmers who rely on service markets can also face uncertainty and risk. For example, service providers may arrive late or not show up at all, which can heavily affect timely production and yields. This risk can be large when service providers yield more market power than farmers (Daum *et al.*, 2020; Daum and Birner, 2017). Mechanization may also create vulnerabilities to shocks from the energy sector (fuel and electricity) (Daum and Birner, 2017; Elverdin, Piñeiro and Robles, 2018). Mechanization often leads to more specialization and less farm diversification, which can reduce resilience (Antle and Ray, 2020; Kansanga *et al.*, 2018). Lastly, the often higher production costs associated with mechanized farming can raise the overall financial risks, as reported by farmers in four African countries (Daum *et al.*, 2020).

5.2 Environmental dimension

Land-use changes, rural landscape changes and biodiversity

Agricultural land-use changes are a major source of anthropogenic greenhouse gases and drivers of terrestrial biodiversity loss (Crippa *et al.*, 2021; Zabel *et al.*, 2019). Mechanization can both reduce and contribute to such land-use changes. As shown above, mechanization can contribute to raising land productivity in many scenarios, reducing the pressure to expand farmland. In Asia, farmland use stagnated during the last decades as mechanization became more widespread. However, mechanization can also facilitate land expansion, i.e. in more land-abundant countries. In such countries, farmland expansion can be a rational choice for farmers, particularly where other inputs are expensive (see Section 5.1). Where farmland comes from converting pristine land, both the aggregated economic benefits and environmental trade-offs can be pronounced (Daum *et al.*, 2020; Pingali, 2007). While there is much evidence of mechanized farmers cultivating more land (see Section 5.1), it is often unclear whether this land comes from reducing fallows, purchasing land from other farmers, or the conversion of pristine land. Daum *et al.* (2020) found evidence of mechanization contributing to land expansion at the cost of forest and savannah in four African countries, with potential high implications for biodiversity conservation and climate change (Searchinger *et al.*, 2015). In Latin America, the conversion of the Cerrado savannah, which entailed large biodiversity losses, would not have been possible without the use of large tractors (de Oliveira *et al.*, 2017). Importantly, farmland expansion can also happen irrespective of mechanization.

Tractors can fundamentally change the face of rural landscapes (Daum *et al.*, 2020; Kansanga *et al.*, 2019, 2020). To facilitate the efficient use of large tractors, farmers often remove trees, hedges, rocks and streams and enlarge and re-shape plots to become rectangular, leading to a loss of farmland diversity, mosaic landscapes (i.e. highly diverse landscapes with various types of ecosystems) and agrobiodiversity (Daum *et al.*, 2020; Kansanga *et al.*, 2019). In many countries, service providers mostly serve farmers who have cleared their plots from trees and tree stumps (Daum and Birner, 2017; Kansanga *et al.*, 2020). In Ghana, Kansanga *et al.* (2018) found that tractors change cropping patterns from crops such as sorghum and millet to easy-to-mechanize crops such as maize and rice. In Ethiopia, Berhane *et al.* (2020) found mechanization to be associated with lower crop diversity. Mechanization does not always have negative effects on on-farm biodiversity. Biodiversity-enhancing practices such as no-till planting basins, intercropping and rotations are often not adopted by farmers because they are very labour-intensive (Dahlin and Rusinamhodzi, 2019; Daum *et al.*, 2022b).

Soil compaction and erosion

Healthy soils are key for sustainable agrifood systems. There is widespread concern that mechanization using (heavy) tractors and inappropriate implements can lead to soil erosion and compaction causing soil degradation and declining yields (FAO and AUC, 2018; Keller *et al.*, 2019). Such concerns have to be taken very seriously given the already widespread land degradation (although mostly not due to mechanization) and the often shallow topsoil in tropical and subtropical low- and lower-middle-income countries. Soil compaction depends on machinery weights, the number of passes and soil types. Soil compaction due to heavy mechanization has been observed across the world (Hamza and Anderson, 2005; Keller *et al.*, 2019). Soil erosion can occur in the absence of mechanization but exaggerated soil erosion problems due to mechanized tillage have been observed in several African countries (Benin, 2015; Daum *et al.*, 2020) and in Latin America and the Caribbean (Elverdin *et al.*, 2018).

A particular concern is the use of disc ploughs, which can lead to hardpans and massive soil erosion where rainfalls are heavy (Daum and Birner, 2020). Soil erosion can also result from the removal of farm trees and changing cropping patterns as a response to mechanization (Kansanga *et al.*, 2020). Soil compaction and erosion can be greatly reduced with sound technical and agronomic solutions (see Section 6).

Fossil energy use and renewable energy

Another concern related to mechanization is that it relies on the use of fossil energy (Daum and Birner, 2020). This criticism neglects that both human and animal power also depends on energy (in the form of food and feed). Moreover, renewable energy is increasingly used to power mechanization activities along the value chain, in particular stationary activities. For example, solar power may be used for irrigation, cooling and refrigeration (for livestock products, fruits and vegetables), drying, but also agro-processing activities such as milling, threshing, husking, hulling and pressing (IFC, 2019).

5.3 Social dimension

Food security

Achieving food security is a key goal of sustainable development. People are food secure when they "at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their food preferences and dietary needs for an active and healthy life" (CFS, 2012). Mechanization can affect all four pillars of food security, which are 1) availability; 2) accessibility; 3) utilization and 4) stability (FAO, 2008). In many situations, mechanization contributes to safeguarding or raising the availability of food (e.g. by affecting yields, cropping intensities, farmland and food loss) (see Section 5.1). Mechanization can also enhance accessibility, e.g. by improving the incomes of farmers, many of which suffer from poverty and hunger (see Section 5.1). Mechanization can also help to keep production costs at bay (Diao, Takeshima and Zhang, 2020; Pingali, 2007), benefiting poor net-food-buying rural and urban households, which spend 50–70 percent of their budgets on food (Diao, Headey and Johnson, 2008) and often cannot afford healthy diets (Herforth *et al.*, 2020). Mechanization can affect utilization where it helps to improve food safety (see Section 5.1). Mechanization can also improve food security outcomes by reducing the physical requirements related to manual farming, which are associated with large energy requirements and can lead to calorific energy shortages (Daum and Birner, 2021; Ogwuike *et al.*, 2014). Irrigation, processing, preservation and storage technologies affect the stability pillar of food security (see Section 5.1).

However, in some cases, mechanization may also have negative effects on food security. Kansanga *et al.* (2019) found that, in Ghana, the use of tractors triggered the clearing of trees, some of which provide fruits and nuts, affecting the availability of some food groups and therefore dietary diversity. Kansanga *et al.* (2018) found that mechanized farmers focus on easy-to-mechanize cereal crops, such as maize. In Ethiopia, Berhane *et al.* (2020) found a correlation between mechanization and lower crop diversity. In contrast, Daum *et al.* (2020) found that mechanization increases crop diversity because farmers have more farmland to cultivate different crops. Importantly, households may be able to offset (or more than offset) any potential drop in farm diversity by buying food from markets. In many cases, mechanization may benefit some but not others. For example, while the conversion of savannah and forests allows the expansion of agricultural production, benefiting the respective farmers, it may affect the availability of wild foods, which can be important for other rural residents. The stability pillar of food security may be affected where mechanization contributes to land degradation (Daum *et al.*, 2020).

Well-being and health

Well-being and health are important social goals of sustainability transformations. Manual farming is associated with backbreaking work, which can undermine well-being and health (Sims and Kienzle, 2006). This drudgery is particularly high under tropical conditions and will likely be intensified by climate change (Dasgupta *et al.*, 2021). Mechanization can help to reduce the drudgery associated with manual farming as well as allow for more leisure time (Benin, 2015; Daum and Birner, 2021; Daum, Capezzone and Birner, 2021; Theis *et al.*, 2019). Pingali (2007) describes how mechanical milling, a power-intensive and laborious task which has spread across the world, has released farm family labour, "especially women from the arduous task of de-husking, pounding and milling grain, often on a daily basis" (p. 2800). In a study of four African countries, the reduction of labour burden and the freeing of time for non-farm activities were mentioned as the top positive effects associated with mechanization as perceived by rural residents (Daum *et al.*, 2020). The heavy toil associated with farming can also prevent adults from carrying out care activities and food preparation, negatively affecting the well-being, food security and health of children (Johnston *et al.*, 2018). Mechanization may be of particular relevance to reducing child labour in agriculture (FAO and IFPRI, 2021), which affects 112 million children, negatively affecting their well-being and health as well as the ability to play or go to school (Daum, Capezzone and Birner, 2021; ILO, 2021). Mechanization may also affect mental health as it can be associated with higher social status (Daum *et al.*, 2020) and increased resilience, as shown above. Furthermore, mechanization may negatively affect farmers' mental health if they struggle to repay debts taken to finance machinery or mechanization services. Operator comfort and safety are growing concerns where humans interact with machines. In a survey in Ghana, Aikins and Barkah (2012) found that only 5 percent of operators wore close-fitted clothing, 50 percent wore heavy-duty boots and all tractors sampled lacked rollover protective structures. Also in Ghana, Aikins and Kyere (2012) found that 36 percent of the operators had no valid license to operate any car, truck or tractor at all.

Equity

Large farms typically have higher motivation and opportunity to mechanize (see Section 4.3). Institutional and technological innovations, discussed in detail in Section 6, can greatly minimize the subsequent mechanization divide but mechanization still tends to be more common on large farms across much of the world (e.g. Berhane *et al.*, 2020; Elverdin, Piñeiro and Robles, 2018; Gulati and Juneja, 2020; Takeshima, 2017). The earlier adoption of technologies by large farms can give them a comparative advantage over small ones, which can lead to a more unequal distribution of land and wealth (Binswanger, 1986). A growing advantage of large farms due to mechanization was found, for example, in Indonesia (Yamauchi, 2016) and China (Wang *et al.*, 2016). In land-scarce countries, small farmers are then likely to experience competition in land markets and may be displaced where land rights are poorly established (Pingali, 2007). Pingali (2007) has shown that tractor use has led to the displacement of tenant farmers in several Asian countries.

In land-abundant countries, mechanized farms may grow without direct immediate effects on non-mechanized farmers (Houssou and Chapoto, 2014). However, land disparities still rise and the future farmland area expansion potentials of non-mechanized farmers are affected (Pingali, 2007). In Ghana, Kansanga *et al.* (2018) have shown that mechanized farmers expand their production by renting out less land to non-native farmers and by appropriating communal lands, foreclosing farmland expansion by poorer households and future generations. However, mechanization does not always disadvantage small farms. Takeshima and Lawal (2020) argue that in Nigeria, tractors "seems to be helping smallholders survive and become more productive, rather than inducing their exit from farming" (p. 446). Moreover, equity concerns are less problematic where mechanized farmers expand by acquiring land from farmers who voluntarily exit farming as part of structural transformation processes (Pingali, 2007). There can be economic gains when less productive farms make space for more productive farms and land consolidation becomes possible (Fuglie *et al.*, 2019; Pingali, 2007).

Gender

Improving the status of women is intrinsically valuable as well as key to achieving several other SDGs (Antle and Ray, 2020). With women shouldering a large share of the agricultural labour burden, one could expect them to benefit much from agricultural mechanization. However, mechanization comes with opportunities as well as risks for women, in particular with regards to the level of access and impacts on labour. Croppenstedt *et al.* (2013) found female-headed households (i.e. households where women are the head and no other male adults are present in the household) to have – by far – less access to motorized mechanization in all 13 studied countries from across the Global South. Women have also been shown to have less access to mechanization as compared to men in several country case studies (e.g. Ahmed and Takeshima, 2020; Daum *et al.*, 2020; Daum and Birner, 2017; Fischer *et al.*, 2018; Kirui, 2019; Njuki *et al.*, 2014; Theis *et al.*, 2019). This can be due to social norms and unfavourable socioeconomic conditions faced by female-headed households who, for example, have smaller and more scattered plots and lower access to credit (Ahmed and Takeshima, 2020; Badstue *et al.*, 2020; Croppenstedt, Goldstein and Rosas, 2013; Daum and Birner, 2017; van Eerdewijk and Danielsen, 2015; Grassi, Landberg and Huyer, 2015; Kansanga *et al.*, 2019; Theis *et al.*, 2019). However, women are not always disadvantaged. In China, Ma (2018) found that female-headed households were more likely to use farm machines.

Household access to mechanization can positively or negatively affect women's labour burden, depending on which crops and tasks are mechanized, the original allocation of labour and second-round effects (Doss, 2001). In many examples, mechanization has reduced the large labour burden associated with farming for women. In India, mechanized tillage benefited women more than men and reduced female labour by 22 percent between 1999 and 2011, mainly because of lower weeding requirements (Afridi, Bishnu and Mahajan, 2020). This pattern has also been observed in several African countries (Baudron, Nazare and Matangi, 2019; Daum, Capezzone and Birner, 2021). Women can also benefit from mechanized processing, a task predominantly conducted by women (Pingali, 2007). The reduction of women's workloads gives women time for other agricultural activities (e.g. livestock keeping or gardening), off-farm work and leisure, as well as for care activities, which can improve the nutrition and education of children (Johnston *et al.*, 2018; Theis *et al.*, 2019).

There are also several studies which suggest that women have not benefitted from mechanization due to households first mechanizing "male" crops (often cash crops) and activities (often more power-intensive activities such as land preparation) (Doss, 2001; Sims, Hilmi and Kienzle, 2016). Van Eerdewijk and Danielsen (2015) found that, in four African countries, mechanization focuses on male-dominated activities as women are constrained in articulating their demand for the mechanization of activities pursued by them due to a lack of empowerment. Mechanization may also lead to a higher workload for women. In many areas, men have focused on more power-intensive and women on more control-intensive activities (Afridi, Bishnu and Mahajan, 2020; Doss, 2001). The sequential adoption of mechanization starting with power-intensive activities can raise the workload for not yet mechanized control-intensive activities such as weeding, harvesting and processing (Afridi, Bishnu and Mahajan, 2020; Doss, 2001; Takeshima and Lawal, 2020). Pingali (2007) reports on the gender effects of mechanical threshers. Before mechanization, men mainly carried out manual threshing since it requires a large amount of physical strength. With mechanization, threshing became less laborious, and women had to take over the task, while men pursued more lucrative off-farm work. Even where mechanization efforts focus on “female” crops (e.g. those for home consumption) and activities, women do not always turn out to benefit. This is because women can lose their decision-making power over “female” crops and activities once they are mechanized and their labour is no longer needed (Carranza, 2014; Daum, Capezzone and Birner, 2021; van Eerdewijk and Danielsen, 2015; Fischer *et al.*, 2018). However, there are also cases where mechanization has empowered women by reducing their dependence on male labour and allowing them to pursue “male” crops and activities (Daum *et al.*, 2020; Fischer *et al.*, 2018).

6 Innovations for smallholder mechanization

Technological and institutional innovations are key to making agricultural mechanization available to smallholder farmers. Technological innovations include smaller-sized machinery such as small four-wheeled tractors and two-wheeled tractors (see Section 6.1). Institutional innovations include a wide range of asset-sharing arrangements such as service markets and cooperative solutions (see Section 6.2). Digital tools may help to address some of the challenges typically associated with such asset-sharing arrangements.

6.1 Technological innovations

Technological solutions such as small four-wheel tractors and two-wheel tractors were a key factor in reducing the mechanization divide in Asia (Bhattarai *et al.*, 2020; Diao, Takeshima and Zhang, 2020; Win, Belton and Zhang, 2020). Two-wheeled tractors are more profitable and adapted to small farm sizes, can manoeuvre around tree stumps and stones, are easier to operate, maintain and repair, and are more viable for microfinance (Baudron *et al.*, 2015; Kahan, Bymolt and Zaal, 2018). Some scholars also see scope for two-wheeled tractors in Africa, although others argue that two-wheeled tractors are associated with a large labour burden and struggle to work the drier and harder soils of mostly rainfed Africa (Daum and Birner, 2020). Baudron *et al.* (2015) argue that two-wheeled tractors are sufficiently powerful to pull rippers and direct seeders for mechanized conservation agriculture. Small four-wheel tractors may also be of relevance for African mechanization, which Diao *et al.* (2020) argue to be held back by a historical bias towards large-scale tractors.

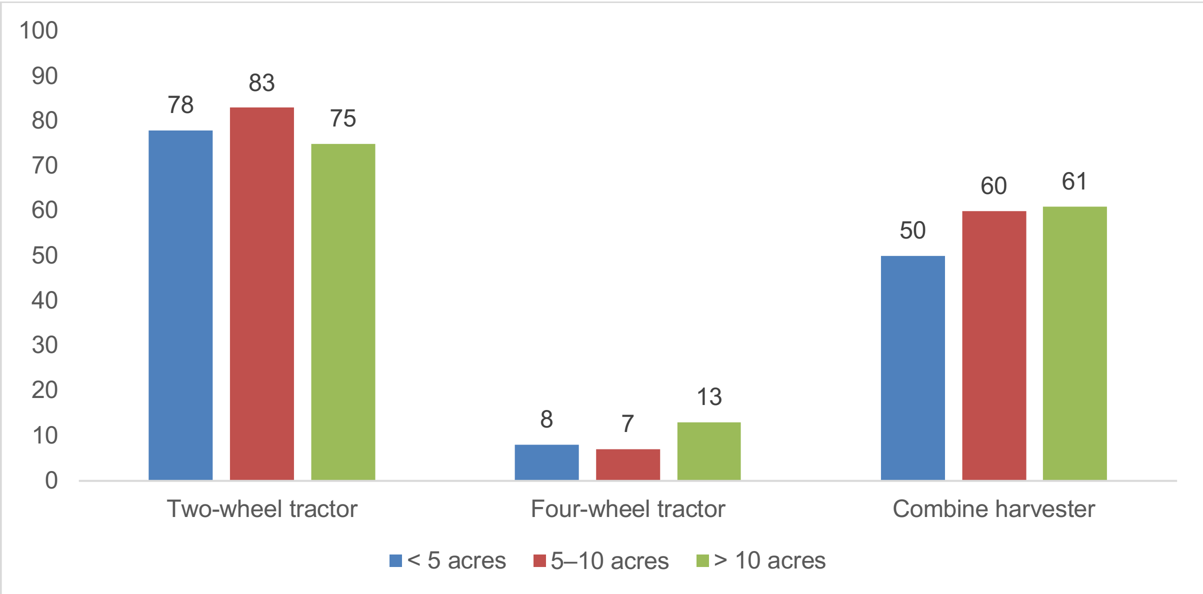
While considered outdated by some (FAO and AUC, 2018), others see continued scope for animal traction in parts of the world (Daum *et al.*, 2022c, 2022a; Thierfelder, 2021). In Asian countries, animal traction has played a large role until very recently (Diao, Takeshima and Zhang, 2020). Diao *et al.* (2020) argued that the familiarity with draught animals and the existence of respective service markets have facilitated the adoption of tractors and the emergence of tractor service markets. In parts of Africa, animal traction is still widespread and even on the rise (Diao, Takeshima and Zhang, 2020). Norman *et al.* (1988) argued that bypassing the animal traction stage on the mechanization ladder is difficult; however, this leapfrogging has happened in several countries. With ample pasture and cheap feed, the use of draught animals can be the rational choice for farmers. Draught animals can also provide meat, milk, hide, manure and biogas (Pearson and Vall, 1998).

However, the use of draught animals has risks, in particular in the absence of reliable support infrastructure (e.g. veterinary services) and the climate crisis. Animal traction requires farmers to have enough pastures or cropland (and labour) to produce feed. With increasing pressure on pastures and farmlands, farmers typically shift towards motorized mechanization. This is bound to happen, for example, in Ethiopia, which has a long culture of animal traction but where the prices for animal traction have doubled in the last two decades (Berhane *et al.*, 2020). In some world regions, in particular in central Africa, animal traction never evolved due to a high prevalence of animal disease (Alsan, 2015; Mrema, Kahan and Agyei-Holmes, 2020; Norman *et al.*, 1988).

6.2 Institutional innovations

Institutional innovations can also enable smallholder farmers to access mechanization. Asset-sharing arrangements have emerged across the Global North (Daum, Huffman and Birner, 2018; Olmstead and Rhode, 1995) and Global South (Pingali, 2007). Mechanization service markets are of particular importance. Such markets benefit both machinery owners and customers. Machinery owners can spread the fixed costs associated with the purchase of machinery and customers can access machinery that they cannot afford to buy. Service markets play a key role in driving and making mechanization inclusive in Asia (Cramb and Thepent, 2020; Diao, Takeshima and Zhang, 2020; Zhang, Yang and Reardon, 2017). In Myanmar, the use of tractors for land preparation and combine harvesters for harvesting/threshing is only marginally higher among larger farmers thanks to vibrant service markets (see Figure 4).

Figure 4. Mechanization across farm size groups, Myanmar



Source: Win, M.T., Belton, B. & Zhang, X. 2020. Myanmar's rapid agricultural mechanization: Demand and supply evidence. *In* X. Diao, H. Takeshima & X. Zhang, eds. *An evolving paradigm of agricultural mechanization development: How much can Africa learn from Asia?* Washington, DC, IFPRI. https://doi.org/10.2499/9780896293809_04

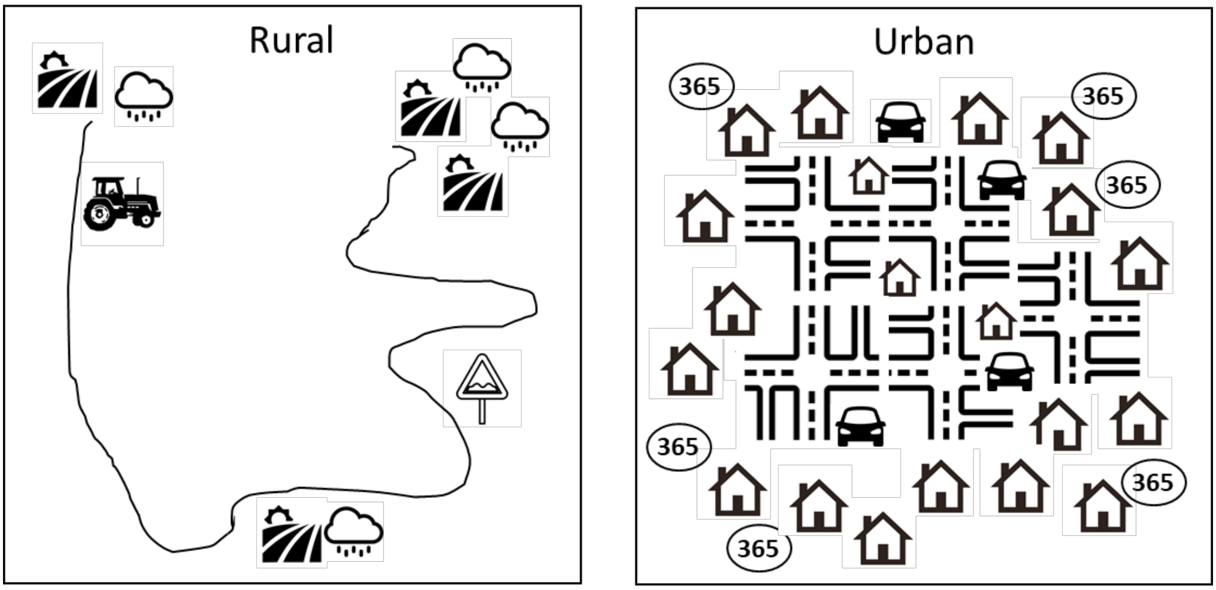
However, mechanization service markets can be undermined by several challenges, which have hampered such markets in some world regions. In Zambia, Adu-Baffour *et al.* (2019) found that only half of the tractor owners who purchased tractors in a private sector scheme with the specific aim to serve smallholder farmers offered services. Mechanization service markets can be undermined by high transaction costs where farmers have small and fragmented plots and where infrastructure is poor (Daum *et al.*, 2021). In many farming systems, farmers also demand mechanization services only for a few weeks per year and usually at the same time due to shared rainfall and temperature patterns, an effect that is particularly pronounced in semi-arid, rainfed farming systems. Service providers can increase utilization rates by offering different types of seasonal services (e.g. land preparation, harvesting, processing and transportation); however, farmers may not demand such services due to the sequential adoption of mechanization (Diao, Takeshima and Zhang, 2020). Another way to increase utilization rates is seasonal migration to areas with different rainfall and temperature patterns. Migratory service provision is popular in many Asian and some African countries but can be undermined by poor infrastructure and border issues, which is a widespread problem in many African countries (Berhane *et al.*, 2020; Diao *et al.*, 2014; Diao, Takeshima and Zhang, 2020; Takeshima and Lawal, 2020). There can also be a considerable risk of machinery damage. For instance, in many African countries, farmers are opening new land where there is a high prevalence of tree stumps and stones but lack the means to carefully clear it (Daum and Birner, 2017; Diao, Takeshima and Zhang, 2020).

Such challenges can also lead to the exclusion of some types of farmers, in particular poor farmers and women (Cabral and Amanor, 2022; Daum and Birner, 2017). In Ghana, Daum and Birner (2017) found that many tractor owners are reluctant to serve smallholder farmers and Cossar (2016) found that farmers without social capital and networks can be excluded from service markets. For smallholder farmers, accessing mechanization service markets can be associated with uncertainty, risks, dependencies and unequal power relations where competition is limited (Daum and Birner, 2017). To combat this, smallholder farmers can group themselves and contact service providers jointly to reduce transaction costs or rely on agents who pool them for a small fee (Adu-Baffour, Daum and Birner, 2019; Daum and Birner, 2017). In some countries, service provision is organized as part of out-grower schemes of downstream value chain actors (Daum and Birner, 2017; Ströh de Martínez, Feddersen and Speicher, 2016).

Asset-sharing strategies are easier to set up for stationary and less time-bound activities. For example, mechanized milling has spread across the world for many decades (Pingali, 2007). Farmers may also jointly purchase machinery as part of cooperative arrangements. Cooperative ownership is widespread for stationary activities such as grain milling (Pingali, 2007). However, joint ownership structures for machinery for mobile activities (e.g. tractors for land preparation) can be heavily affected by governance challenges. For example, free-rider problems may undermine careful operation and maintenance (i.e. members may not do maintenance in the hope that others will do it) and the synchronous timing of farming operations may lead to conflicts (Daum and Birner, 2017). Cooperative arrangements may also be dominated by wealthy farmers and exclude poor and female farmers and other often marginalized groups (Daum and Birner, 2017).

Asset-sharing arrangements had emerged across the world in the pre-digital era (Binswanger and Donovan, 1987; Olmstead and Rhode, 1995; Pingali, 2007). However, digital tools promise to greatly improve such arrangements. For example, digital tools such as GPS tracking devices and fleet management software can be used by service providers to reduce problems related to the supervision of machinery operators, which are particularly high for migratory service providers. Digital tools following the model of Uber-type solutions for ride-hailing, which are on the rise across much of the Global South, promise to reduce the large transaction costs faced by smallholder farmers and by machinery service providers. Examples of such tools are Hello Tractor in Nigeria, TROTRO Tractor in Ghana and EM3 in India.

Figure 5. Agricultural mechanization services versus urban ride-hailing



Source: Daum, T., Villalba, R., Anidi, O., Mayienga, S.M., Gupta, S. & Birner, R. 2021. Uber for tractors? Opportunities and challenges of digital tools for tractor hire in India and Nigeria. *World Development*, 144: 105480. https://doi.org/10.1016/j.worlddev.2021.105480

While such tools hold great promises, they face various challenges associated with the nature of rural and agricultural markets that urban ride-hailing markets do not face (see Figure 5). In urban areas, the density of customer demand is higher, both across space and time. In rural areas, farmers demand services often only once or twice per season and farmers from the same areas demand service at the same time, as discussed above. Moreover, urban infrastructure tends to be more developed as compared to rural infrastructure. Lastly, ownership rates of mobile/smartphones and digital connectivity, literacy and trust are typically higher in urban areas. To address these challenges, Uber-for-tractor tools often rely on the use of analogous solutions such as booking agents to pool smallholder farmers against a commission (Daum *et al.*, 2021). As such, their advantages for customers over more traditional forms of organizing service markets are still more limited than often assumed (Daum *et al.*, 2021). Daum *et al.* (2021) suggest that such tools predominantly benefit large and migratory service providers who travel across agroecological zones and unknown territories as these tools can be used for fleet and customer management (Daum *et al.*, 2021). This may change in the future, however, and digital tools are likely to become a key cornerstone for inclusive agricultural mechanization.

7 Conclusions and pathways towards sustainable transformation

Mechanization comes with many opportunities but also some risks for the sustainable transformation of agrifood systems in low- and lower-middle-income countries. Accompanying efforts from private, public and third sector actors are needed to create an enabling environment for agricultural mechanization (see Section 7.1) and to harness opportunities and mitigate risks associated with mechanization to ensure sustainable and inclusive agricultural transformation (see Section 7.2).

7.1 Addressing barriers by creating an enabling environment for agricultural mechanization

Across the world, private mechanization markets evolved once an economic demand for technologies to substitute human labour emerged and such markets manage to effectively provision machines, spare parts and repairs services (Diao, Takeshima and Zhang, 2020; Pingali, 2007). Public efforts to directly promote mechanization have a poor track record – both historically and contemporarily – and are likely to lead to market distortion (Daum and Birner, 2017; Pingali, 2007). However, public sectors can play a catalytic role in mechanization by creating an enabling environment for market-led mechanization (Daum and Birner, 2017; Diao, Takeshima and Zhang, 2020; Pingali, 2007). In many cases, regional cooperation can facilitate the setup of governance structures, in particular for small countries (FAO and AUC, 2018). Third-sector actors can also play a role in assisting mechanization efforts (Daum and Birner, 2017). Governments can support mechanization with both mechanization-specific and more general policies and investments that are key for agricultural development. General policies and investments may affect mechanization patterns more than policies and investments directly tailored towards mechanization (Binswanger and Donovan, 1987). Such policies and investments relate to tenure security, transportation, communication and electricity infrastructure, and general credit markets and exchange rate policies:

- **Improving land tenure security:** Insecure land tenure creates disincentives for farmers to invest in farming and buy agricultural machinery that takes several years to pay off, and can also restrict their access to credit as land titles cannot be used as collateral (Binswanger and Rosenzweig, 1986; Diao, Takeshima and Zhang, 2020). Enhancing land tenure security raises farmers' incentives to intensify and mechanize, and allows farmers to use their land as collateral. This enhances their access to credit markets, which is key for mechanization and is usually difficult to access by smallholder farmers (Binswanger, 1986; Pingali, 2007). In Myanmar, land tenure reforms have significantly raised the possibility for farmers to use bank loans to purchase machines (Diao, Takeshima and Zhang, 2020; Win, Belton and Zhang, 2020).
- **Improving transportation, communication and electricity infrastructure:** Poor infrastructure can lead to high transaction costs for farmers accessing production factor, input and output markets, reducing their incentives and possibilities to intensify and produce for markets and invest in technology such as mechanization. Improving transportation infrastructure also enables farmers to better connect with urban markets, which are growing across much of the Global South, increasing both the incentives and possibilities to intensify and mechanize. Improving transportation infrastructure reduces the transaction costs for farmers accessing machinery, spare parts, repairs and fuel, and facilitates the emergence

of migratory service markets (Daum and Birner, 2017; Mrema, Baker and Kahan, 2008). In many Asian and Latin American and Caribbean countries, transportation and communication infrastructure has improved rapidly during the last decades, while African infrastructure has remained poor in many parts (Antle and Ray, 2020). Improving transportation infrastructure reduces the transaction costs for farmers accessing machinery, spare parts, repairs and fuel. Improving communication infrastructure can help to reduce the transaction costs related to both input and output markets. By improving the electricity supply, governments can support the local manufacturing sector as well as facilitate the uptake of mechanization technologies such as pumps for irrigation and machinery for processing and preservation (Cramb and Thepent, 2020; Diao, Takeshima and Zhang, 2020; Justice and Biggs, 2020). Governments may want to specifically focus on the potential of renewable energy to power mechanization down the value chain (IFC, 2019).

- **Improving general credit markets and exchange rate policies:** Credit is crucial for mechanization as machinery is expensive and can take several years to pay off. Smallholder farmers' access to credit is usually limited due to a lack of collateral (e.g. land titles) and high transaction costs, among other challenges (Binswanger and Rosenzweig, 1986; Daum and Birner, 2017; Ströh de Martínez, Feddersen and Speicher, 2016; Van Loon *et al.*, 2020). Diao *et al.* (2020) argue that African farmers in particular face high financial constraints. Alongside lack of access, prohibitive interest rates often make it impossible to use credit to finance tractors (Daum and Birner, 2017; Diao, Takeshima and Zhang, 2020; Ströh de Martínez, Feddersen and Speicher, 2016; Van Loon *et al.*, 2020). General policies related to interest rates can heavily influence mechanization patterns (Binswanger and Donovan, 1987). Credit policies have played a key role in Asian mechanization (Cramb and Thepent, 2020; Diao, Takeshima and Zhang, 2020). Likewise, general policies related to exchange rates can also heavily influence mechanization patterns by affecting the import costs for machinery, spare parts and fuel (Binswanger and Donovan, 1987; Daum and Birner, 2017; Diao, Takeshima and Zhang, 2020).

Next to supporting mechanization with general policies and investments, policymakers can also pursue mechanization-specific policies and investments, in particular related to knowledge and skills development, quality assurance, applied research, import policies and finance, among others. These are described in the following bullet points:

- **Building knowledge and skills:** Machinery manufacturers, owners, operators, technicians and farmers all need knowledge and skills on how to create, manage, operate, maintain and repair agricultural machinery (Bishop-Sambrook, 2005; Daum and Thoelen, 2019; Diao, Takeshima and Zhang, 2020; FAO and AUC, 2018). Despite the fact that a lack of knowledge and skills can heavily undermine the profitability and sustainability of mechanization, knowledge and skills are often poorly promoted (Daum and Birner, 2017; Houssou *et al.*, 2013; Van Loon *et al.*, 2020). Regarding machinery operation, Houssou *et al.* (2013) showed that 86 percent of tractors in Ghana are affected by frequent and long-lasting breakdowns due to poor maintenance and a lack of skilled operators and mechanics. Also in Ghana, Aikins and Haruna (2012) found that 48 percent of the tractors broke down more than three times per season due to a lack of maintenance and careless operation. Aikins and Kyere (2012) found that 97 percent of operators in Ghana did not follow maintenance rules. Public efforts to build knowledge and skills played a key role during the mechanization history of today's mechanized countries (Daum, Huffman and Birner, 2018). Vocational training centres that combine applied training with theoretical "in-classroom" teaching may be particularly suited to provide the knowledge and skills needed (Daum and Kirui, 2021; Van Loon *et al.*, 2020).

- **Providing mechanisms for quality assurance and developing standards:** A lack of quality assurance in the form of testing and certification of machinery, spare parts and fuels can also undermine mechanization, as it increases the uncertainty and risks associated with the purchase of machinery, spare parts and fuels (Daum, Huffman and Birner, 2018; Diao, Takeshima and Zhang, 2020). A lack of testing and certification may in particular affect local manufacturers who may be less trusted by customers (Daum and Birner, 2017). Testing and certification can be organized by public, market and third sector organizations. Likewise, strengthening the institutions setting standards can support the manufacturing and trade of mechanization technologies (FAO and AUC, 2018).
- **Conducting applied research and development:** Mechanization (but not automation) hinges less on public basic science research than some other agricultural technologies (Evenson and Binswanger, 1987) and many technological advances are driven by private research and development (Diao, Takeshima and Zhang, 2020; FAO and AUC, 2018). Governments can support private research and development with the most appropriate institutions as well as conduct or fund applied research to develop technical, agronomic and economic solutions for locally adapted and sustainable mechanization (Daum and Kirui, 2021; FAO and AUC, 2018).
- **Improving import policies and procedures:** High import duties and tedious customs procedures can affect mechanization supply. In Asia, the removal of import restrictions greatly contributed to mechanization (Diao, Takeshima and Zhang, 2020; Pingali, 2007). In Africa, machinery is now exempted from import duties in many countries although such duties remain in some countries (Diao, Takeshima and Zhang, 2020; FAO and AUC, 2018; Van Loon *et al.*, 2020). Moreover, while machinery is mostly exempted, spare parts are often charged with (sometimes high) duties, which can undermine the sustainability of mechanization. Tedious and slow import procedures and unofficial duties can also affect machinery imports (Daum and Birner, 2017; Diao, Takeshima and Zhang, 2020). Reducing import duties for machinery and spare parts and improving customs procedures can help to increase investments in machinery and spare parts and lower mechanization costs (Daum and Birner, 2017; Diao, Takeshima and Zhang, 2020; FAO and AUC, 2018).
- **Improving mechanization finance:** Limited access to finance often limits the scaling-up of mechanization. Unlike seeds, fertilizers and pesticides, mechanization technologies are lumpy assets that typically require costs to be spread across several years (Daum and Birner, 2017; Diao, Takeshima and Zhang, 2020; Ströh de Martínez, Feddersen and Speicher, 2016)). To purchase machinery, farmers can use cash, savings, or financial services (Ströh de Martínez, Feddersen and Speicher, 2016). Investment loans are the most common solution to finance mechanization but can be undermined by high costs and a lack of securities (Daum and Birner, 2017; Ströh de Martínez, Feddersen and Speicher, 2016). In the case of security issues, contract-based securities, loan guarantee schemes, joint liability groups and leasing can be options (Ströh de Martínez, Feddersen and Speicher, 2016). In the case of cost issues, matching grants and “smart” subsidies (which do not distort markets) may play a role (Ströh de Martínez, Feddersen and Speicher, 2016). Some Asian countries used such tools to enhance farmers’ access to credit (Bhattarai *et al.*, 2020; Diao, Takeshima and Zhang, 2020). Value chain finance may also be a way forward (Ströh de

Martínez, Feddersen and Speicher, 2016). Also, as shown by the historic example of the Raiffeisen model (Turvey, 2017) and the more recent experiences of India (Bhattarai *et al.*, 2020), cooperative credits can play a key role in financing mechanization. While much attention focuses on loans, saving products can also play a role and insurance products may become necessary for larger machinery (Ströh de Martínez, Feddersen and Speicher, 2016). Next to farmers and service providers, local manufacturers and maintenance and repair shops may also need access to loans (Daum and Birner, 2017; FAO and AUC, 2018). Mechanization finance should be led by market actors and guided by commercial viability as public efforts to directly finance mechanization often struggle with large governance challenges (Meyer, 2011; Ströh de Martínez, Feddersen and Speicher, 2016).

7.2 Ensuring that mechanization contributes to sustainable agrifood systems transformation

Section 5 has shown various sustainability synergies and trade-offs related to agricultural mechanization. Sustainability synergies arise due to positive effects related to food security, poverty reduction and health and well-being, among many others. Possible sustainability trade-offs concern unemployment effects, biodiversity loss from farmland expansion and simplification, soil compaction and erosion, disparities between large and small farms and gender disempowerment, among others. These trade-offs can be minimized or avoided altogether with accompanying policies and investments, examples of which are detailed below.

- **Safeguarding against negative employment effects:** Mechanization can have a wide range of different effects on rural employment, both positive and negative (see Section 5.1.). Empirical evidence suggests that mechanization typically does have not negative effects on unemployment where it emerges as a response to market forces such as rising rural wages due to structural transformation and where it replaces unpaid family labour (Binswanger, 1986; Daum and Birner, 2020). However, unemployment effects are typically the results of mechanization being artificially pushed by large-scale public efforts to import and subsidize machinery, suggesting that governments should avoid such efforts (Pingali, 2007).
- **Avoiding biodiversity loss from farmland expansion and simplification:** Mechanization can lead to farmland expansion at the expense of forests and savannah, contributing to climate change and biodiversity loss (see Section 5.2). Land-use planning and monitoring can be used to minimize or avoid such effects by protecting land that is particularly valuable for climate change mitigation and biodiversity conservation (Daum *et al.*, 2020; Daum and Birner, 2020). Negative effects can also be reduced with more sustainable cultivation strategies such as crop-livestock-forestry systems, which come with fewer climate effects and allow for more biodiversity (Alves, Madari and Boddey, 2017; Daum *et al.*, 2020; Daum and Birner, 2020). In some countries, governments have successfully minimized farmland expansion with land use planning and monitoring. However, in other countries, public interventions contributed to such negative effects, for example, where they supported large-scale block farming schemes or land investments. Section 5.2 also showed that mechanization can be associated with farmland simplification to facilitate the use of large tractors. Land-use planning and monitoring can be used to preserve mosaic landscapes, which are considered to be key for biodiversity conservation. Scale appropriate mechanization, where machines are adapted to farm size and not the opposite can also help to reduce negative environmental effects (Baudron, Nazare and Matangi, 2019; Baudron *et*

al., 2015). Small four-wheel or two-wheel tractors are also better able to manoeuvre around traditional landscape features and on-farm trees as compared to large tractors.

- **Safeguarding against land degradation:** Mechanization can lead to soil compaction and erosion. Knowledge and skills development efforts can help ensure operating practices that reduce soil compaction and erosion. Lighter machinery can also mitigate soil compaction. Mechanized conservation agriculture can reduce soil erosion using rippers or direct planters to replace ploughs. Jaleta *et al*. (2019) even argue that farm mechanization and reduced tillage to avoid erosion are not antagonistic but synergistic. Conservation agriculture with minimal soil disturbances, crop rotation and permanent soil covers can reduce soil erosion by up to 99 percent (Labrière *et al.*, 2015). Conservation agriculture appears as the way forward for agriculture across much of the Global South (Baudron *et al.*, 2015; FAO and AUC, 2018) but locally adapted solutions are needed to avoid some of the challenges (Giller *et al.*, 2009). Applied technical and agronomic research can help to explore mechanization solutions that best fit local agroecological conditions. Governments can also apply higher duties and taxes or otherwise restrict access to implements that are likely to be harmful to soils (Daum and Birner, 2017; FAO and AUC, 2018).
- **Addressing disparities between large and small farms:** Technological and institutional innovations can help to drive mechanization and ensure it is inclusive for smallholder farmers (see Section 6). Technological solutions such as smaller-sized machinery, two-wheeled tractors and even animal traction can play a key role. Farmers themselves can best choose which mechanization solutions best fits their local agroecological conditions and governments should help create a level playing field. Institutional solutions such as mechanization service markets have been key for smallholder mechanization across the world. Governments can support the emergence of such service markets by improving rural infrastructure, providing good legal conditions, facilitating border crossings and providing service providers with knowledge, skills development and business training (Daum and Birner, 2017; FAO and AUC, 2018). Third-sector organizations such as farmer-based organizations can help to reduce the transaction costs related to working with smallholder farmers, for example, by organizing farmers into groups (Adu-Baffour, Daum and Birner, 2019). Digital tools can address some challenges associated with service markets such as reducing transaction costs. Government can facilitate the use of such tools with efforts to build digital connectivity, literacy and trust (Daum *et al.*, 2021). While technological and institutional innovations can reduce mechanization divides, mechanization may still favour larger farms. Governments have to ensure that small farms are protected from encroachment or get compensation when they voluntarily leave their land to work in non-farm sectors by improving land tenure security (Pingali, 2007).
- **Ensuring that women benefit from mechanization:** Mechanization can both positively and negatively affect women; hence, integrating women in mechanization efforts is key to avoiding negative effects (Ströh de Martínez, Feddersen and Speicher, 2016). Women often have less access to mechanization, partly because of owning smaller and more fragmented plots and having less access to agricultural markets, credits and extension, among others. Policies and investments that address these disadvantages (e.g. policies improving women's land rights or access to credit and extension) will also help to increase women's access to agricultural mechanization. Another reason for women to have less access to mechanization is social norms. Entry points to change this may be gender awareness campaigns (e.g. featuring women who are successful service providers or operators) and

supporting women's mechanization groups where women collectively manage machinery while having access to both finance and knowledge and skills development (van Eerdewijk and Danielsen, 2015). More research is needed to better understand how women's access to mechanization can be improved. Women may also be less able to express their mechanization needs due to a lack of empowerment and can be affected by second-round effects on their labour burden (Doss, 2001; van Eerdewijk and Danielsen, 2015; Sims, Hilmi and Kienzle, 2016). Policies and investments enhancing women's power can help them to better express their needs and avoid negative second-round effects or ensure appropriate compensation. Public research and development can focus on gender-friendly mechanization technologies, tailoring the design of technologies to the needs of women (FAO and AUC, 2018).

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