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REVIEW ARTICLE

Mechanization and sustainable agri-food system transformation in the Global South. A review

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Abstract
There is an urgent need for agri-food system transformation to achieve global sustainability goals. Innovations can play a key role in this transformation but often come with both sustainability synergies and trade-offs. One such innovation is agricultural mechanization, which is spreading rapidly in parts of the Global South and is high on the policy agenda in others. The rapid spread of mechanization is fundamentally changing the character of agri-food systems in the Global South, with both positive and negative effects. However, while some of these effects have been well explored, no study so far has systematically reviewed the sustainability synergies and trade-offs associated with mechanization, undermining necessary accompanying research and policy efforts. This review provides an overview of the progress toward mechanization across the Global South, identifies drivers and barriers, assesses sustainability synergies and trade-offs, and discusses options to maximize sustainability outcomes. The review is the first to holistically assess the potentials and risks of agricultural mechanization for the sustainable transformation of agri-food systems in the Global South, taking into account all pillars of sustainability. The review suggests that agricultural mechanization is needed to make agri-food systems more sustainable concerning various economic and social aspects, such as labor productivity, poverty reduction, food security, and health and well-being. However, there are also sustainability risks concerning environmental aspects such as biodiversity loss and land degradation, and economic and social concerns related to lacking inclusiveness and growing inequalities, among others. A wide range of technological and institutional solutions is identified to harness the potential of agricultural mechanization for sustainable agri-food system transformation, while at the same time minimizing the risks. However, more efforts are needed to implement such solutions at scale and ensure that mechanization contributes to agri-food systems that respect all pillars of sustainability.

Keywords Technological change · Tractors · Agricultural development · Sustainable development · Sustainability studies

Contents

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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. Despite hard work, this type of life was often associated with 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 ards by around 4000 BC (Mazoyer and Roudart 2006) and water-powered mills emerged in China by around 1000 BC (Pingali 2007). Technological change has accelerated during the past two centuries with the emergence of steam plows and threshers and the rise of fossil energy–powered tractors (see also Fig. 1), harvesters, and processing machines, among others (Daum et al. 2018; Hurt 1982). Agricultural mechanization has enabled societies across the world to gradually decouple agricultural production from agricultural labor, freeing them from the heavy physical toil of farming.

But progress has not been even across the world. Northern America and Europe are fully mechanized and many countries in Asia and Latin America and the Caribbean made considerable progress (Diao et al. 2020). In Sub-Saharan Africa, despite signs of rapid mechanization in selected pockets, 80% of farmers are still believed to rely on manual labor (Daum and Birner 2020; Diao et al. 2020; FAO and AUC 2018). The unequal progress toward mechanization explains the dramatic differences in agricultural labor productivity across the world, which in turn helps in part to explain world income inequality (Gollin et al. 2014; Fuglie et al. 2019). The agricultural value-added per worker in Northern America is 66 times higher than that in Sub-Saharan Africa, 15 times higher than in Latina America and the Caribbean, and 10 times higher than in East Asia (World Bank 2022). While farmers in the USA obtain 1470 kg of maize per hour worked, Kenyan farmers obtain only 1.2 kg (Gollin 2019).

Fig. 1 Tractor in Zambia (Photo Credit: Daum).

There is a broad consensus that innovations are key to realizing more sustainable agri-food systems (e.g., Herrero et al. 2020; Webb et al. 2020). Agri-food system innovations are typically associated with a complex set of synergies and trade-offs across the three—social, economic, and environmental—pillars of sustainability (e.g., Antle and Ray 2020). Proponents of mechanization typically highlight the potential of mechanization to improve social and economic aspects of agri-food systems, in particular, its potential to raise agricultural labor productivity, and subsequently, increase incomes, and reduce poverty (FAO and AUC 2018; Sims and Kienzle 2006). There are also strong arguments regarding its potential to reduce the heavy toil of farming (Daum and Birner 2021; FAO and AUC 2018), which will be exaggerated with climate change (Dasgupta et al. 2021), and which is often shouldered by unpaid family members, including women and children (Lowder et al. 2019; Takeshima and Vos 2022). But there are also concerns related to mechanization. One fear is that large and wealthy farms are more likely to afford the necessary machines and then grow at the expense of smallholder or tenant farmers (e.g., Pingali 2007). Another concern is that mechanization excludes women (e.g., Croppenstedt et al. 2013; Fischer et al. 2018; Theis et al. 2019). A long-standing concern is that mechanization causes rural unemployment (Binswanger and Donovan 1987). There are also concerns that mechanization can undermine environmental sustainability by contributing to deforestation, savannah conversion, farmland simplification, and land degradation (e.g., Daum et al. 2020; Daum and Birner 2020; Kansanga et al. 2019; Keller et al. 2019).

Understanding sustainability synergies *and* trade-offs is key to guiding and designing policy action that will harness the opportunities and mitigate the risks associated with mechanization and ensure it contributes to sustainable agri-food systems. This review, therefore, aims to contribute to a better understanding of the opportunities and risks related to agricultural mechanization and of its role in sustainable agri-food system transformation in the Global South. Based on these insights, a wide range of technological and institutional solutions to harness the potential of agricultural mechanization for sustainable agri-food system transformation, while at the same minimizing the risks, will be identified and discussed.

Section 2 will provide an overview of key terms related to agricultural mechanization. Section 3 will provide an overview of the trends of agricultural mechanization in the Global South. Section 4 discusses some major drivers and barriers to mechanization, which can help to explain different mechanization patterns across the Global South. Section 5 explores the opportunities and risks of agricultural mechanization for sustainable agri-food system transformation. Section 6 focuses on the role of technological and institutional innovations to make agricultural mechanization inclusive for smallholder farmers. Section 7 provides policy recommendations on how to create an enabling environment for agricultural mechanization and ensure it contributes to sustainable agri-food system transformation.

2 Key terms

Agricultural mechanization refers to the substitution of human labor with animal or mechanical power in the crop, livestock, aquaculture, and agroforestry value chains (Daum and Kirui 2021). Farm mechanization describes the substitution of human labor on the farm whereas agricultural mechanization spans the whole agricultural value chain (Daum and Kirui 2021; FAO and AUC 2018; see Fig. 2). Agricultural mechanization should not be equated with the use of tractors but tractors are a cornerstone of farm mechanization as they can pull and push implements such as plows, 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 oxen and donkeys), whereas agricultural motorization focuses on the use of mechanical power, which can be run with fossil or renewable energy (FAO and AUC 2018). There are many linkages between mechanization and irrigation. The mechanization of irrigation can help to harness the potential of irrigation, and, vice versa, irrigation can be an important catalyst for mechanization by enabling intensification, as further discussed below

Pingali et al. (1987) 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 (Pingali et al. 1987; Pingali 2007). This is because power-intensive activities are associated with a higher labor burden and because control-intensive activities 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. The ability to share assets also depends on whether an activity is time-bound (e.g., planting, harvesting of cereals) or allows more flexibility (e.g., milling).

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, followed by the Middle East and North Africa as well as Asia, which is catching up rapidly, while progress in Sub-Saharan Africa has been limited (see Fig. 3). As the following sections will show, mechanization

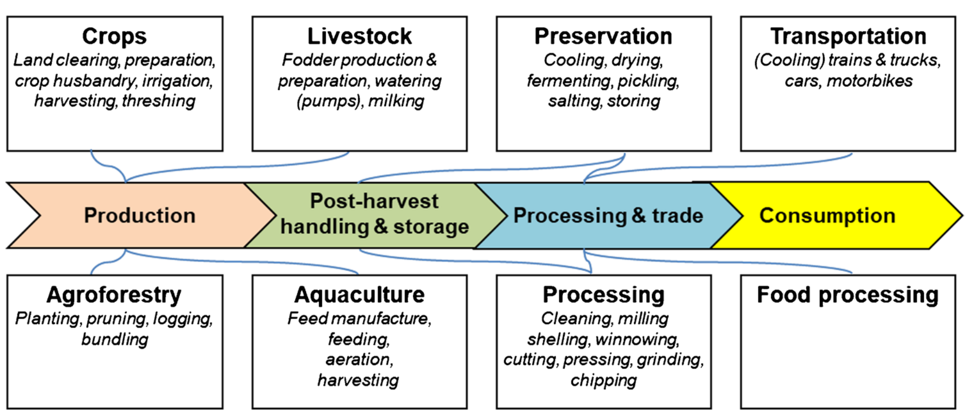

Fig. 2 Activities along the value chain that can be mechanized (Adapted from Daum and Kirui 2021).

Table 1 Classification of agricultural activities by power and control intensity and degree of mobility. Based on Pingali (2007)

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

trajectories within world regions such as Asia, Africa, and Latin America and the Caribbean can be diverse as geographical, biophysical, and socioeconomic characteristics are heterogeneous. Importantly, while the number of tractors per 1000 farm workers is often used as a proxy for overall mechanization since cross-country data are available, the underlying data are partially patchy and outdated. Moreover, the number of tractors per 1000 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 allow the sharing of tractors among many farmers. 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).

3.1 Asia

Asia was the least mechanized in terms of tractors of all world regions in the 1960s (see Fig. 3). However, while Asian farmers used few tractors, their farming systems were already quite intensified and the use of animal traction was common for land preparation and irrigation (e.g., to drive Persian Wheels), which facilitated the rapid mechanization in the subsequent decades (Diao et al. 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 et al. 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). Tractors were first used mainly for power-intensive land preparation but later, labor shortages and rising rural wages have been driving the mechanization of control-intensive planting, pest control, harvesting, and processing (Diao et al. 2020). In Asia, the establishment of public irrigation infrastructure and the spread of private irrigation technologies played a key role in intensification, and subsequently, overall mechanization development (Cramb and Thepent 2020; Diao et al. 2020; Takeshima et al. 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) (Belton et al. 2021; Diao et al. 2020). Bhattarai et al. (2020) estimate that today land preparation on up to 90% of the farmland in India is motorized. In rice production, the share of farmland prepared with machinery is above 85% in Bangladesh, China, Sri Lanka, and Myanmar (Abeyratne and Takeshima 2020; Ahmed and Takeshima 2020; Win et al. 2020; Zhang et al. 2017). In contrast, only around 23% of the farmers in mountainous Nepal use tractors and power tillers—but 46% do so in Nepal's less-sloping Terai zone (Takeshima and Justice 2020). Mechanization continues to be more limited regarding harvesting but combine harvesters are on the rise in some countries (Diao et al. 2020; Yang et al. 2013).

	Sub-Sahara Africa	East Asia	Asia South	Middle East and North Africa	Latin America
1960	0.7	0.2	0.2	11.0	4.9
1980	1.1	1.9	2.2	25.9	26.6
2000	1.0	2.3	10.2	38.0	50.7
Latest	1.0	11.1	21.9	47.6	66.0

Fig. 3 Tractor use per 1000 farm workers in different world regions (Fuglie et al. 2019). Note: Latest is mostly 2009 but in some cases much earlier.

Farm mechanization is increasing despite small farm sizes, which are often perceived to be a constraint to mechanization, thanks to technological and institutional innovations (Bhattarai et al. 2020; Diao et al. 2020). While larger farmers generally had a head-start regarding mechanization, these innovations facilitated mechanization among smallholder farmers (Diao et al. 2020). Technological innovations include small four-wheel tractors and two-wheel tractors (Diao et al. 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). In many rice-growing areas in Asia, multifunctional two-wheel tractors were key to power irrigation pumps, which led to a virtuous cycle between intensification and mechanization (Cramb and Thepent 2020; Takeshima et al. 2020). Sophisticated market-led service markets have evolved in various Asian countries (Diao et al. 2020; Justice and Biggs 2020). In Bangladesh, only 4% of farm households own tractors but 89% hire them, of which 80% own less than 1 ha of land (Diao et al. 2020). In China, migratory service providers are traveling across agro-ecological zones with fleets of combined harvesters (Yang et al. 2013; Zhang et al. 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 small mini and power tillers), shallow tubewells, 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 et al. 2020). Mechanization in Asia countries was mainly driven by private markets (Diao et al. 2014, 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 et al. 2020).

3.2 Africa

African agri-food systems are the least mechanized of all world regions. Around 10% of 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 centers, 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 a lack of investments in 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 et al. 2020; Pingali et al. 1987; Pingali 2007; see also Section 4).

Farming systems are now evolving and rural wages are rising in some areas, leading to mechanization in selected pockets (Daum and Birner 2020; Diao et al. 2020; FAO and AUC 2018). Tractors are in particular concentrated in Northern Africa and South Africa (Mrema et al. 2008). Kirui (2019) estimated the share of tractor use to be as high as 57% in Egypt and 70% in South Africa. Some Sub-Saharan African countries have also seen progress toward mechanization. In Ghana, up to one-third of farm households use tractors for some farm operations (especially for land preparation), with mechanization levels being as low as 2% in parts of the forest zone and as high as 88% in the savannah zones (Diao et al. 2020). In Tanzania, up to 14% of the farmland is cultivated with tractors, with mechanization levels being highest in large-scale commercial farming areas (Mrema et al. 2020). In Nigeria, 7% of farmers use tractors (Takeshima and Lawal 2020). In most other African countries, the number of tractors is "extremely low" (Mrema et al. 2008). Kirui (2019) estimated the share of tractor use among farmers to be below 1% in Cameroon, Niger, and Senegal. In Ethiopia, around 1% 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 harvesting (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% of farmers use animal traction for land preparation (Berhane et al. 2020). In Tanzania and Nigeria, this share stands at around 25% (Mrema et al. 2020; Takeshima and Lawal 2020). On average, 15% 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 have been popular for many decades. Unlike in Asia where 37% of the land is irrigated, only 6% of the farmland is irrigated in Africa, mainly in Northern Africa, Sudan, and South Africa, and only a fraction of this land is irrigated with modern technologies (Malabo Montpellier Panel 2018). In many parts, irrigation is held back by a lack of public investments in irrigation infrastructure and a lack of affordable small-scale irrigation technologies, among others (Diao and Takeshima 2020; Malabo Montpellier Panel 2018). 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 focus less on addressing such supply-side constraints by creating a conducive environment for market-led mechanization and more on efforts to directly promote mechanization (e.g., by pursuing large-scale programs to import machinery and distribute it at 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 the 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 also a growth of private-sector channels supplying machinery, including both used and new machinery, and including efforts from global machinery manufacturers such as AGCO, John Deere, and Mahindra, as well as smaller companies from the Global South (Daum and Birner 2020). Across Africa, local manufacturing sectors are increasingly widespread for simple types of equipment. Private mechanization service markets are also growing in several countries (Berhane et al. 2020; Daum and Birner 2020; Diao et al. 2014).

3.3 Latin America and the Caribbean

Latin America 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 the Global North (Elverdin et al. 2018). In the 1960s, there were 5 tractors per 1000 farm workers. In the 2010s, this ratio increased to around 65 tractors (see Fig. 3). This represents, on average, a 4% 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 toward 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 1000 farm workers is highest in Uruguay and Argentina—followed by Brazil, Venezuela, Chile, Panama, and Mexico (Elverdin et al. 2018; Martín-Retortillo et al. 2019). The country that witnessed the most rapid mechanization progress was Brazil, with an annual growth rate of 7% (Martín-Retortillo et al. 2019). In contrast, countries such as Bolivia, El Salvador, Peru, and Colombia, among others, all started at a low level and witnessed limited progress concerning tractorization (Elverdin et al. 2018; Martín-Retortillo et al. 2019). In general, Latin America and Caribbean countries are characterized by the coexistence of large-scale, highly mechanized farms and smallholder farms, which are often not as mechanized, especially in remote and hilly areas (Antle and Ray 2020; da Silva et al. 2018; ECLAC et al. 2017; Elverdin 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, for example, with public programs to facilitate access to credit at low-interest rates and with tax exemptions, in various countries such as Argentina, Costa Rica, Ecuador, and Peru (ECLAC et al. 2017; Elverdin et al. 2018). Moreover, several countries have exempted agricultural machinery from import duties, for example, Peru (ECLAC et al. 2017). However, in many countries, especially 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 et al. 2018). In Brazil and Mexico—and to some degree, Argentina—strong agricultural machinery manufacturing sectors have emerged that also export both to the region and globally, including large machinery such as tractors and harvesters (Elverdin et al. 2018). In some countries especially such as Argentina, agricultural mechanization service markets play a great role in smallholder mechanization (Elverdin et al. 2018).

4 Drivers and barriers

Mechanization patterns are affected by both drivers and barriers on the demand and supply sides. Drivers include changing land and labor 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 bio-physical conditions (see Section 4.3), and a lack of enabling environments (and Section 4.4).

4.1 Land and labor 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 labor 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 et al. 2020). The theory of induced agricultural innovations suggests that innovations are driven by changes in the relative endowments and prices of production factors such as land and labor (Hayami and Ruttan 1970). Private actors develop and adopt technologies that help to substitute "relatively scarce and hence expensive factors of production" (Ruttan 1977, pp. 204–205). Public sectors facilitate this process with accompanying institutions (Ruttan and Hayami 1984). In labor-scarce areas, farmers first adopt labor-saving technologies (e.g., mechanization, and herbicides). In land-scarce areas, farmers first adapt 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 American countries with larger farm sizes. However, it fails to explain the high degree of mechanization in labor-abundant, land-scarce Asia as compared to historically labor-scarce, land-abundant Africa (Diao et al. 2020; Elverdin et al. 2018; Pingali 2007).

The theory of farming system evolution has been developed by Boserup (1965) and Ruthenberg (1980) and adopted for mechanization by Pingali et al. (1987). According to this theory, in land-abundant, labor-scarce areas, the rational choice of farmers is not to mechanize but to practice extensive shifting cultivation, which is associated with low labor requirements (Boserup 1965; Diao et al. 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 the incentive to produce surplus food (Nin-Pratt et al. 2014). Increasing population densities cause a transition toward annual and multiple cropping (Boserup 1965; Ruthenberg 1980). This intensification is associated with higher labor requirements and triggers the mechanization of the most labor-intensive farming steps even where rural wages are still low (Diao et al. 2020; Pingali et al. 1987). Farmers tend to first mechanize using animal traction—unless this option is restricted by animal diseases such as trypanosomosis vectored by tse tse flies (Alsan 2015)—and later tractors when animal traction becomes exceedingly expensive due to pressure to convert grazing land to cropland (Pingali et al. 1987; Ruthenberg 1980).

Farming system evolution helps to explain continental differences. Densely populated Asian countries witnessed high levels of farming system evolution in the 1960s, a major pre-condition for rapid mechanization in the following decades, which was further pushed due to intensification as part of the Green Revolution (Diao et al. 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 et al. 2020; Pingali 2007). Mechanization was only widespread on large commercial farms, a legacy of colonization, and as part of state-supported block farm and tractor hire schemes, many of which soon collapsed (Pingali et al. 1987; Pingali 2007). In the last few decades, cropping intensities have been increasing in all but a few countries (Binswanger-Mkhize and Savastano 2017; Diao et al. 2020; Heinimann et al. 2017; Sebastian 2014; van Vliet et al. 2012). The shift toward permanent cropping is slowly increasing the demand for mechanization; however, 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 labor out of agriculture, leading to labor shortages, rising wages, and opportunity costs (Diao et al. 2014, 2020). Structural transformation is typically associated with both a falling share of employment in agriculture and with urbanization as industries and service sectors are more likely to be located in urban areas.

Many Asian countries witnessed structural transformation, urbanization, and rapidly rising rural wages in the last decades (see also Fig. 4). For example, real rural wages tripled between 1992 and 2008 in Vietnam (Takeshima et al. 2020) and rose by 42% between 2011 and 2016 in Myanmar (Win et al. 2020). In China, farm wages grew between 8 and 10% annually from 1997 to 2016, leading to a sharp rise in mechanization and a halving of the labor days per ha (Wang et al. 2016). In Nepal, the wage of rural laborers for plowing rose by 86% for men and 195% 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; Pingali et al. 1987; Pingali 2007). In many Asian countries, this is now

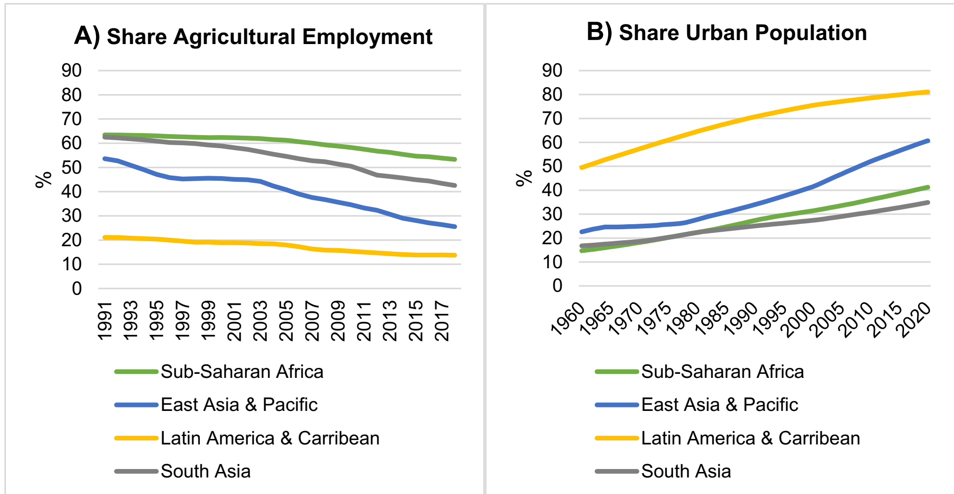

Fig. 4 Share of agricultural employment (**A**) and share of the population residing in urban areas (**B**) in different world regions (World Bank 2022).

leading to full mechanization, as exemplified by the rise of combined harvesters (Diao et al. 2020).

In Africa, labor is moving out of agriculture more slowly and urbanization rates are increasing less quickly than in other world regions (see Fig. 4). However, there are also growing rural labor constraints in several countries (Diao et al. 2020). In Ethiopia, structural transformation has caused a rise in the real wages of unskilled laborers in rural areas by more than 50% in the last two decades (Berhane et al. 2020). In Ghana, new opportunities in the nonfarm sectors have led to rising rural wages, causing labor costs to now account for 45% 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 (Daum and Birner 2020; Diao et al. 2020). Labor 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 HIV/AIDS), among others (Bishop-Sambrook 2005; Jayne et al. 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, e.g., toward "easy-to-cook" cereals such as wheat and maize, which are more labor-intensive (but also easier to mechanize) than roots and tubers (Diao et al. 2020; Tschirley et al. 2015). All of this incentivizes farmers to intensify production and generates the incentives and purchasing power needed to adopt labor-saving mechanization. This can be observed in many Asian countries (Diao et al. 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 et al. 2020; Jayne et al. 2010).

4.3 Technology costs, farm sizes, and agroecological conditions

Mechanization patterns are also shaped by endogenous factors such as technology costs. Falling technology costs have greatly contributed to mechanization in Asia (Diao et al. 2020). In Africa, machinery was historically imported from Europe and North America, and technology costs were high. Technology costs are now falling with growing competition from manufacturers from Asia (especially India and China) and South America (especially 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 per hectare 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 et al. 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 the economics of scales, disadvantaging smallholder farmers who operate on small and fragmented plots (Antle and Ray 2020). It is therefore not surprising that there is both historic (e.g., Binswanger and Donovan 1987) and contemporary (e.g., Berhane et al. 2020; Elverdin et al. 2018; Takeshima 2017) evidence that large farms often mechanize earlier than small farms. However, small farm sizes are not necessarily an adoption barrier 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 et al. 2020). Such mechanization service markets are on the rise across various African countries (Adu-Baffour et al. 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 bio-physical factors can also shape mechanization patterns (Daum et al. 2022a, b, c). 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, as mentioned above. 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 et al. 2020). For example, soils with greater bulk densities tend to require more farm power (Binswanger and Donovan 1987), unless farmers use no-till land preparation techniques. 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 Asia, easy-to-mechanize cereal crops such as wheat and maize are dominating 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 the limited market size. Tree-based cropping systems are also difficult to mechanize (Cramb and Thepent 2020; Pingali et al. 1987). 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 et al. 2020; Pingali et al. 1987).

4.4 Enabling environments

Agricultural mechanization technologies are embodied in private goods and as such private markets have a strong incentive to provide mechanization where there is demand (Sunding and Zilberman 2001). Mechanization has been driven by private markets in Latin America, the Caribbean, and 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 programs (Daum and Birner 2020; Diao et al. 2020). Such efforts have been typically short-lived due to a 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 (AUC and FAO 2019; Daum and Birner 2017; Pingali et al. 1987; Pingali 2007). Public programs are likely to fail where private markets are missing due to a lack of demand and can crowd out private actors (Daum and Birner 2020; Pingali 2007). However, markets can also be undermined by market failures and governments can have a key role to support markets (Daum and Birner 2017; Diao et al. 2020). Governments played a key role in supporting private sector mechanization in Northern America and Europe (Daum et al. 2018) and Asia (Belton et al. 2020; Diao et al. 2014, 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 programs crowding out private investments.

5 Sustainability synergies and trade-offs

Agri-food 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 agri-food system transformation, including regarding economic (see Section 5.1), environmental (see Section 5.2), and social (see Section 5.3) aspects. The major potential sustainability synergies and trade-offs identified in this review are depicted in Fig. 5. 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 (bio-physical, geo-political, socio-economic, and cultural factors) and accompanying practices, policies, and investments.

5.1 Economic dimension

5.1.1 Labor productivity, labor use, and employment

Substituting human power with animal power or mechanical power can greatly enhance agricultural labor productivity (Binswanger 1986; Diao et al. 2020; Hayami and Ruttan 1970; Sims and Kienzle 2006). Labor productivity describes the output per unit of labor input. Mechanization affects the labor inputs but can also affect outputs (see below). Studies on changes in land and labor productivity across the world during the past decades reveal strong similarities between agricultural labor productivity and the mechanization patterns described in Section 3 (see e.g., Fuglie et al. 2019).

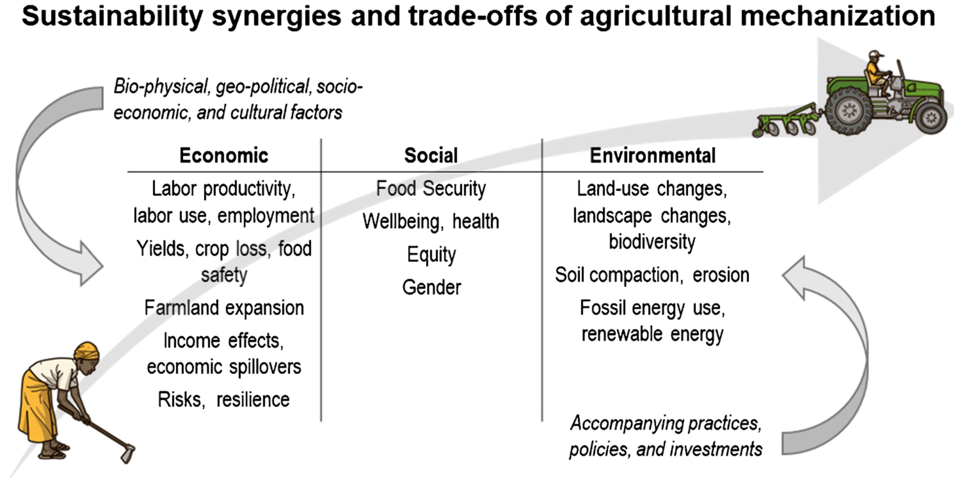

Fig. 5 Synergies and trade-offs of agricultural mechanization regarding the three pillars of sustainability (economic, social, and environmental). Note: Fig. 5 shows that synergies and trade-offs depend on both context (bio-physical, geo-political, socio-economic, and cultural factors) and accompanying practices, policies, and investments.

In a review of labor use effects of tractors, Pingali et al. (1987) reported that 22 of 24 studies have found a reduction in labor once tractors were used rather than draught animals—with 12 studies reporting labor reductions above 50%. Sims and Kienzle (2016) show that primary tillage using manual tools requires around 500 labor hours per hectare as compared to only 60 h using animal traction and 1 to 2 h using tractors. In a recent study in Ethiopia, tractor-using households used less than half the labor per ha as non-tractor-using households (Berhane et al. 2020). In a study in Zambia, farm families with mechanized land preparation used 645 labor hours per hectare of maize on average compared to 1133 among non-mechanized households (Adu-Baffour et al. 2019). Such households achieved twice the gross margin per hour of farm labor (Adu-Baffour et al. 2019). Processing, preserving, storage, and transportation technologies can equally raise labor productivity (Daum and Kirui 2021). Moreover, motorized irrigation (pumps) can significantly help farm households to save time and labor (Malabo Montpellier Panel 2018). However, while mechanization raises labor productivity, the overall labor input can decline, stagnate, or increase. In the Zambian study above, labor input per hectare declined but the overall labor input per farm declined only marginally since the household achieved higher yields and expanded farmland, both of which increased labor demand during subsequent farming steps. Similarly, in a study in Côte d'Ivoire, tractor use led to higher labor productivity and labor input per hectare (Mano et al. 2020).

There are concerns that mechanization leads to unemployment, especially in countries that are perceived to have surplus labor (Binswanger and Donovan 1987; Daum and Birner 2020; Pingali 2007). Theoretical and empirical evidence suggests that unemployment effects are complex depending on the farm steps being mechanized, second-round effects on yields and farmland expansion, the former source of labor, and non-farm employment opportunities, among others (Binswanger 1986; Daum and Birner 2020; Pingali 2007). In the following points, some typical scenarios are illustrated:

- *Increasing labor input, increasing employment*: As shown above, mechanization can lead to an overall increase in labor input. Mechanization is often adopted in a sequential process, starting with power-intensive operations such as land preparation. Labor demand 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 labor use by 12% due to area expansion and higher input use. Similar second-round effects have been observed in Botswana (Panin 1995), Ghana (Benin 2015; Cossar 2019; Kirui 2019), Niger, Zimbabwe (Kirui 2019), and Zambia (Adu-Baffour et al. 2019). Pumps for irrigation also often raise the demand for labor because cropping intensities and yields increase (Binswanger 1986; Pingali 2007).
- *Declining labor input, no unemployment*: Even where mechanization leads to an overall reduction in labor inputs, this does not necessarily cause unemployment, for example when mechanization is a response to structural transformation, during which people leave farming to seek more attractive alternative employment opportunities (Binswanger 1986; Pingali 2007) or when mechanization replaces unpaid family work, including from women and children (Adu-Baffour et al. 2019; Daum and Birner 2020; Pingali 2007).
- *Declining labor input, and 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 in areas without labor shortages, rising wages, and alternative employment opportunities (Binswanger 1986; Pingali 2007).

Mechanization can also lead to employment effects beyond the farm. For example, farm mechanization may affect employment opportunities down the value chain when 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 forward and backward linkages.

5.1.2 Yields, crop loss, and food safety

Agricultural mechanization is often viewed as a technology to "save" labor, with limited effects on land productivity (Binswanger 1986). Where land is available and cheap, using tractors to cultivate more land rather than raising yields is often the rational choice of farmers (e.g., Baudron et al. 2012; Berhane et al. 2020; Bishop-Sambrook 2005; Houssou and Chapoto 2015; Nin-Pratt and McBride 2014). There is also some evidence that replacing draught animals with tractors has limited yield effects (Bhattarai et al. 2020; Pingali 2007). However, it is increasingly acknowledged that mechanization can raise land productivity where it addresses labor bottlenecks, improves agricultural practices (e.g., by enabling better seed placement and higher fertilizer use efficiency), increases cropping frequencies, triggers the adoption of yield-increasing technologies, and reduces crop damages and losses:

- *Addressing labor bottlenecks and shortages*: There is growing evidence regarding how labor bottlenecks and shortages undermine timely and careful seedbed preparation and crop management and hence yields. Seasonal labor bottlenecks and shortages have always been a feature of rainfed agriculture in arid and semi-humid areas where untimely operations can have large yield effects (Ruthenberg 1980). Baudron et al. (2015) show that delaying planting reduces yields by up to 1% per day. In Ethiopia, labor constraints are responsible for up to 50% of yield gaps (Silva et al. 2019). Baudron et al. (2019a, b) found that a lack of farm power is a key factor explaining yield gaps in Eastern and Southern Africa.
- *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 significantly increase cropping intensity (Diao et al. 2020; Pingali 2007; Pinstrup-Andersen and Hazell 1985; Singh 2001; Tetlay et al. 1990; Verma 2006). Mechanization can also affect the adoption of yield-increasing technologies such as improved seeds, fertilizer, and pesticides (Bhattarai et al. 2020; Diao et al. 2020; Ma et al. 2018; Mano et al. 2020; Nin-Pratt and McBride 2014; Takeshima and Lawal 2020). Some forms of mechanization are also primarily adopted to raise or safeguard yields. Irrigation can increase or stabilize yields where rains are unpredictable and droughts are common (Malabo Montpellier Panel 2018; Pingali 2007). Precision irrigation can increase both yields and water use efficiency (Malabo Montpellier Panel 2018; Parthasarathi et al. 2018; Zhang et al. 2021). In Asia, irrigation played a key role in agricultural intensification (Diao et al. 2020). For example, in Thailand, public and private investments in irrigation enabled a shift to double cropping, which was a key "impetus for mechanization" (Cramb and Thepent 2020). In Nigeria, there is evidence that mechanization levels are higher on farms with higher production nearby formal irrigation facilities (Takeshima and Lawal 2020). Across Africa, it is estimated that small- and large-scale irrigation could raise agricultural production by 50% (You et al. 2011), although irrigation potentials are not equally distributed across the continent and are lower than those in Asia (Diao et al. 2020; Malabo Montpellier Panel 2018).
- *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 et al. 2018). A study in Kenya found that 95% of potato damage and losses were attributed to a lack of harvesting technology (Breuer et al. 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%. In Ethiopia, combined harvesters increase yields by around 20% as harvesting and threshing are otherwise constrained by a lack of labor and the use of rudimentary tools (Berhane 2020).

Mechanization can also help to reduce post-harvest food losses and contribute to food safety. Preservation and storage technologies (e.g., dryers, and cold storage) can considerably reduce food losses and enhance food safety (Salvatierra-Rojas et al. 2017). Processing technologies can also reduce food losses (Elverdin et al. 2018). In Africa, a lack of processing technologies has been estimated to cause an annual loss of one million tonnes of rice (Malabo Montpellier Panel 2018). Transportation technologies (e.g., trucks, cars, motorbikes) can also reduce food losses. Technologies for preservation and storage, processing, and transportation are particularly useful regarding perishable food such as fish, fruits, vegetables, meat, and dairy products (Daum and Kirui 2021). 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).

5.1.3 Farmland expansion

Using manual labor 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 labor 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 plowed using tractors or draft animals is associated with an increase in land cultivated by 14% and 13%, respectively. Also in Ghana, Kansanga et al. (2018a) found that mechanization allowed smallholder farmers to double farm sizes within 10 years (from around 1 to 2 ha). Mechanization has also affected land expansion in Indonesia (Yamauchi 2016) and Brazil (de Oliveira et al. 2017). For the respective households, farmland expansion is beneficial. In Zambia, tractor-using households cultivated double the amount of land and achieved twice the income of non-mechanized farmers (Adu-Baffour et al. 2019). Farmland expansion effects are limited where "pristine" land is either not available or well protected and where larger farms cannot grow at the expense of smaller farms as their land rights are well established. Dummet and Blundell (2021) show that more than 2/3 of agricultural expansion in tropical forests is illegal. Some forms of mechanization could—in principle—reduce farmland requirements as they increase land productivity and reduce food loss, as discussed before, a pattern that may, however, only evolve with parallel set-aside programs.

5.1.4 Income effects and economic spillovers

Farm households typically aim to maximize real net incomes, among other goals. Mechanization can help farmers to increase labor productivity, a key determinant of income (Binswanger 1986; Diao et al. 2020; Fuglie et al. 2019; Hayami and Ruttan 1970). Mechanization can affect labor productivity if it enables yield growth, area expansion, and value addition, and/or if it decreases labor inputs and costs. In a study in Zambia, mechanized households obtained twice the incomes compared to non-mechanized farmers after controlling for covariates (Adu-Baffour et al. 2019). In a study in Nigeria, tractor use raised real incomes by 13% (Takeshima and Lawal 2020). Rising agricultural labor productivity often enables households to allocate time away from agriculture and pursue off-farm work (Daum et al. 2021a; Kansanga et al. 2020; Ma et al. 2018; Theis et al. 2019). Pingali (2007) argues that "poor households benefit the most since the released labor can be reallocated for other income-earning activities or leisure" (p. 2800). Rising farm incomes can lead to spill-over effects from the now more prosperous farmers to the wider rural and urban economy (Christiaensen et al. 2011; Haggblade et al. 2010).

5.1.5 Risks and resilience

Mechanization can increase the resilience of farm households to some types of risks; however, it can also create new vulnerabilities. Mechanization can increase the resilience to health shocks affecting household labor or hired labor, which can severely disrupt agricultural production, with effects on food security and poverty, in particular in already poor households (Jayne et al. 2010). Irrigation technologies increase resilience to climatic shocks, which will become more likely and severe with climate change (Malabo Montpellier Panel 2018). Climate resilience can also be increased as mechanization allows farmers to complete farming activities more quickly and respond more flexibility to changing weather patterns (Elverdin et al. 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.

But mechanization may also create new vulnerabilities. Machines can break down or service providers may arrive late or not at all, which can heavily affect timely production and yields (Daum and Birner 2017). This risk can be especially large where service providers yield more market power than farmers (Daum and Birner 2017; Daum et al. 2020). Mechanization may also create vulnerabilities to shocks from the energy sector (fuel and electricity) (Daum and Birner 2017; Elverdin et al. 2018). Mechanization often leads to more specialization and less farm diversification, which can reduce resilience (Antle and Ray 2020; Kansanga et al. 2018a). 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

5.2.1 Land-use changes, landscape changes, and impacts on 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 besides unfolding mechanization.

However, mechanization can also facilitate land expansion, especially in more land-abundant countries. In such countries, farmland expansion can be a rational choice for farmers, especially 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 farmland expansion by mechanized farmers (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 costs of forest and savannah in four African countries, with potentially 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; Kansanga et al. 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, and agrobiodiversity (Daum et al. 2020; Kansanga et al. 2019). In many countries, service providers mostly serve farmers who have cleared their plots of trees and tree stumps (Daum and Birner 2017; Kansanga et al. 2020). In Ghana, Kansanga et al. (2018a) 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, intercropping, and rotations are often not adopted by farmers because they are very labor-intensive (Daum et al. 2022c; Dahlin and Rusinamhodzi 2019).

5.2.2 Soil compaction and erosion

Healthy soils are key for sustainable agri-food systems. There is a 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 countries of the Global South. 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; Takeshima and Biggs 2020). Soil erosion can occur in the absence of mechanization but exacerbated soil erosion problems due to mechanized tillage have been observed in several African countries (Benin et al. 2015; Daum et al. 2020) and in Latin America and the Caribbean (Elverdin et al. 2018). A particular concern is disc plows, which can lead to hardpans and massive soil erosion, especially where rainfalls are heavy (Daum and Birner 2020). Soil erosion can also be a result of the removal of farm trees and changing cropping patterns due to mechanization (Kansanga et al. 2020). Soil compaction and erosion can be greatly reduced with sound technical and agronomic solutions (see Section 6).

5.2.3 Fossil energy use, renewable energy, and water use

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 and fruits and vegetables), drying, but also agro-processing activities such as milling, threshing, husking, hulling, and pressing (IFC 2019). In the context of irrigation, motorized pumps, which are more powerful than human-powered pumps, can lead to environmental challenges such as groundwater decline and depletion, in particular, where governance challenges were not addressed (e.g., Wada et al. 2012).

5.3 Social dimension

5.3.1 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" (United Nations Committee on World Food Security). 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 low (Diao et al. 2020; Pingali 2007), benefiting poor net-food-buying rural and urban households, which spend 50–70% of their budgets on food (Diao et al. 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 caloric 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. In Ghana, Kansanga et al. (2019) found that the use of tractors triggered the clearing of trees, some of which are providing fruits and nuts, affecting the availability of some food groups and hence dietary diversity. Kansanga et al. (2018a) found that mechanized farmers focus on easy-to-mechanize cereal crops (especially 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 to other rural residents. The stability pillar of food security may be affected when mechanization contributes to land degradation (Daum et al. 2020).

5.3.2 Well-being and health

Well-being and health are important social goals of sustainability transformations. In the absence of mechanization, farming is typically 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 et al. 2021a, b; 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 labor, "especially women from the arduous task of de-husking, pounding and milling grain, often on a daily basis" (p. 2800). Motorized irrigation has also been shown to greatly reduce time spent on fetching water, benefiting in particular women and girls (Malabo Montpellier Panel 2018). In a study in four African countries, the reduction of labor 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 labor in agriculture (Takeshima and Vos 2022). Seventy percent of child labor is in agriculture, affecting the present and future livelihoods of 112 million children (ILO 2021), by negatively affecting their well-being and health as well as the ability to play or go to school (Daum et al. 2021a; ILO 2021). Mechanization may also affect mental health as it can be associated with higher social status (Daum et al. 2021a) 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 is a growing concern when humans interact with machines. In a survey in Ghana, Aikins and Barkah (2012) found that only 5% of operators wore close-fitted clothing and only 50% wore heavy-duty boots and all tractors sampled lacked rollover protective structures. Also in Ghana, Aikins (2012) found that 36% of the operators had no valid license to operate any car, truck, or tractor at all.

5.3.3 Equity

Large farms typically have higher motivation and opportunity to mechanize (see Section 4.3). Institutional and technological innovations 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 et al. 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. (2018b) 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 "seem 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 (Pingali 2007; Fuglie et al. 2019).

5.3.4 Gender

Improving the status of women is intrinsically valuable as well as a key to achieving several other sustainable development goals (Antle and Ray 2020). With women shouldering a large share of the agricultural labor burden, one could expect them to benefit much from agricultural mechanization. However, mechanization comes with risks as well as opportunities for women, in particular concerning the level of access and impacts on labor. Croppenstedt et al. (2013) found female-headed households (especially 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 13 of 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 and Birner 2017; Daum et al. 2020; Fischer et al. 2018; Kirui 2019; Njuki et al. 2014; Theis et al. 2019). This can be due to social norms and unfavorable socioeconomic conditions faced by female-headed households who, for example, tend to have smaller and more scattered plots and lower access to credit (Ahmed and Takeshima 2020; Badstue et al. 2020; Croppenstedt et al. 2013; Daum and Birner 2017; Kansanga et al. 2019; Theis et al. 2019; Van Eerdewijk and Danielsen 2015). However, women are not always disadvantaged. In China, Ma (2018) found that female-headed households were more likely to use farm machines than male-headed ones.

Where households access mechanization, this can positively or negatively affect women's labor burden, depending on which crops and tasks are mechanized, the original allocation of labor, and second-round effects (Doss 2001). In many examples, mechanization has reduced the large labor burden associated with farming for women. In India, mechanized tillage benefited women more than men and reduced female labor by 22% between 1999 and 2011—mainly because of lower weeding requirements (Afridi et al. 2020). This pattern has also been observed in several African countries (Baudron et al. 2019a, b; Daum et al. 2021a). Women can also benefit from mechanized processing, a task predominantly conducted by women (Pingali 2007). Moreover, motorized irrigation has also been shown to greatly reduce the time spent fetching water by women (Malabo Montpellier Panel 2018). 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).

Several studies suggest that women have not benefitted as much 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; Evers and Walters 2001; Sims et al. 2016). Van Eerdewijk and Danielsen (2015) found in four African countries that 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 et al. 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 et al. 2020; Doss 2001; Takeshima and Lawal 2020). Pingali (2007, referring to Ebron 1984) reports on the gender effects of mechanical threshers using an illustrative case from the Philippines. Before mechanization, men mainly carried out this manual task since it requires a large amount of physical strength. With mechanization, threshing became "lighter" 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 labor is no longer needed (Carranza 2014; Daum et al. 2021a; Fischer et al. 2018; Van Eerdewijk and Danielsen 2015). However, there are also cases where mechanization has empowered women by reducing their dependence on male labor 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 types of 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 key factors in reducing the mechanization divide in Asia (Bhattarai et al. 2020; Diao et al. 2020; Win et al. 2020). Two-wheeled tractors may be more profitable and adapted to small farm sizes; can maneuver around tree stumps and stones; are easier to operate, maintain, and repair; and are more viable for microfinance (Baudron et al. 2015; Kahan et al. 2018). Some scholars also see scope for two-wheeled tractors in Africa, although others argue that two-wheeled tractors are associated with a large labor burden and struggle to work the drier and harder soils of mostly rainfed Africa (Daum and Birner 2020; Daum et al 2022b). Baudron et al. (2015) argue that two-wheeled tractors are powerful enough 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 toward 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. 2022b; Thierfelder 2021). In Asian countries, animal traction has played a large role until very recently (Diao et al. 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 or even on the rise (Diao et al. 2020). Pingali et al. (1987) argued that bypassing the animal traction stage on the mechanization ladder is difficult; however, this leapfrogging has happened in several countries. With ample pasture, the use of draught animals can be the rational choice for farmers. Draught animals can also provide meat, milk, hide, manure, and biogas.

However, the use of draught animals can have 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 labor) to produce feed. With increasing pressure on pastures and farmlands, farmers typically shift toward 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, particularly in Central Africa, animal traction never evolved due to a high prevalence of animal disease (Alsan 2015; Mrema et al. 2020; Pingali et al. 1987).

6.2 Institutional innovations

Institutional innovations can also enable smallholder farmers to access mechanization. Asset-sharing arrangements have emerged across the Global North (Daum et al. 2018; Olmstead and Rhode 1995) and Global South (Pingali 2007). Mechanization service markets are of particular importance. 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 et al. 2020; Zhang et al. 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 Fig. 6).

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

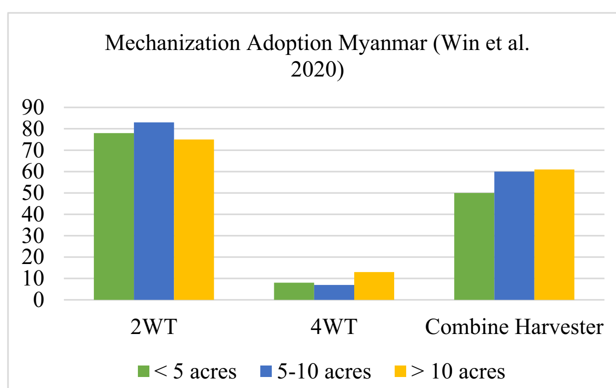

Fig. 6 Adoption rates of different mechanization technologies (two-wheel tractors, four-wheel tractors, and combine harvesters) in different farm size categories in Myanmar (Win 2020).

et al. 2021b). In many farming systems, farmers 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 et al. 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 (Berhane et al. 2020; Diao et al. 2014, 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 yet lack the means to carefully clear it (Daum and Birner 2017; Diao et al. 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, especially where competition is limited (Daum and Birner 2017). 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 et al. 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; de Martínez et al. 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 and the synchronous timing of framing may lead to conflicts (Daum and Birner 2017). Cooperative arrangements may also be dominated by wealthy farmers and exclude poor farmers, female farmers, and other often marginalized groups (Daum and Birner 2017).

Asset-sharing arrangements had emerged across the world in the pre-digital era (Binswagner and Donovan 1987; Olmstead and Rhode 1995; Pingali 2007). However, digital tools hold great promise to 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.

While such tools hold great promises, they face various challenges that urban ride-hailing markets do not face. 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. 2021b). As such, their advantages for customers over more traditional forms of organizing service markets are still more limited than often assumed (Daum et al. 2021b). This may change in the future, however, and digital tools are likely to become a key cornerstone for inclusive agricultural mechanization.

7 Pathways toward sustainable transformation

Mechanization comes with many opportunities but also some risks for the sustainable transformation of agri-food systems in the Global South. 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 labor emerged and such markets managed to effectively provision machines, spare parts, and repair services (Diao et al. 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 distortions (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 et al. 2020; Pingali 2007). Third-sector actors can also play a role in assisting mechanization efforts (Daum and Birner 2017). Governments can support mechanization with both mechanization-specific 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 toward mechanization (Binswanger and Donovan 1986). 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 et al. 2020). Enhancing land tenure security raises farmers' incentives to intensify and mechanize and allows farmers to use their land as collateral, thereby enhancing their access to credit markets, which is key for mechanization, and in particular difficult to access for 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 et al. 2020; Win et al. 2020).
- *Improving transportation, communication, electricity, and irrigation infrastructure*: Poor infrastructure can lead to high (transaction) costs for farmers accessing markets for production factors, inputs, and outputs, 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 et al. 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 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 et al. 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). The experiences of Asia also suggest that investments in public irrigation infrastructure can play a key role in mechanization development (Diao et al. 2020).
- *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 credits 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; de Martínez et al. 2016; Van Loon et al. 2020). Diao et al. (2020) argue that African farmers in particular face high financial constraints. Alongside lack of access, high interest rates often make it impossible to use credits to finance tractors (Daum and Birner 2017; de Martínez et al. 2016; Diao et al. 2020; 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 et al. 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 et al. 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.

- *Building knowledge and skills*: Machinery manufacturers, dealers, owners, operators, technicians, and farmers all need knowledge and skills on how to create, manage, operate, maintain, and repair agricultural machinery (Bishop-Sambrook 2005; Diao et al. 2020; FAO and AUC 2018; Thoelen and Daum 2019). Although 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% 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% of the tractors broke down more than three times per season due to a lack of maintenance and careless operation. Aikins (2012) found that 97% 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 et al. 2018). Vocational training centers that combine applied "on-the-job" 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 et al. 2018; Diao et al. 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, and may be organized across countries. 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 1978), and many technological advances are driven by private research and development (Diao et al. 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 on how to develop technical, agronomic, and economic solutions for locally adapted and sustainable mechanization (Daum and Kriui 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 et al. 2020; Pingali 2007). In Africa, machinery is now exempted from import duties in many countries although they remain in some countries (Diao et al. 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 et al. 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 et al. 2020; FAO and AUC 2018).
- *Improving mechanization finance*: Limited access to finance often constrains 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 et al. 2020; Ströh de Martínez et al. 2016). To purchase machinery, farmers can use cash, savings, or financial services. Investment loans are the most common solution to finance mechanization but can be undermined by a lack of security and high costs (Daum and Birner 2017; Ströh de Martínez et al. 2016). In the case of security issues, contract-based securities, loan guarantee schemes, joint liability groups, and leasing can be options (Ströh de Martínez et al. 2016). In the case of cost issues, matching grants and "smart" subsidies (which do not distort markets) may play a role (Ströh de Martínez et al. 2016). Some Asian countries used such tools to enhance farmers' access to credit (Bhattarai et al. 2020; Diao et al. 2020). Value chain finance may also be a way forward (Ströh de Martínez et al. 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 et al. 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 et al. 2016).

7.2 Ensuring that mechanization contributes to sustainable agri-food 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 women's disempowerment, among others. These trade-offs can be minimized or avoided altogether with accompanying policies and investments:

- *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 not have 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 labor (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 lands, 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 and Birner 2020; Daum et al. 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 et al. 2017; Daum and Birner 2020; Daum et al. 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, when they supported large-scale block farming schemes or land investments. Section 5.2 also shows 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 (highly diverse landscapes with various types of ecosystems), which are considered to be key for biodiversity conservation. Scale-appropriate mechanization, where "machines are adapted to farm size and not the opposite" (Baudron et al. 2019b, p. 154), can also help to reduce negative environmental effects (Baudron et al. 2015, 2019b). Small four-wheel or two-wheel tractors are better able to maneuver 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 disturbance using rippers or direct planters to replace plows. Jaleta et al. (2019) 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% (Labrière et al. 2015). Conservation agriculture appears as the way forward for mechanized 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 bio-physical 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 role (Daum et al. 2022b). Farmers themselves can best choose which mechanization solutions best fit their local 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 and skills development, including business aspects (FAO and AUC 2018; Daum and Birner 2017). 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 in groups (Adu-Baffour et al. 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. 2021b). While technological and institutional innovations can reduce mechanization divides, mechanization may still favor 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 et al. 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 women have less access to mechanization is social norms. Entry points to change this may be gender awareness campaigns (e.g., "show-casing" women who are successful service providers or operators) and supporting women's mechanization groups where women collectively manage machinery with knowledge and skills development and access to finance (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 lacking empowerment and can be affected by second-round effects on their labor burden (Doss 2001; Evers and Walters 2001; Sims et al. 2016; van Eerdewijk and Danielsen 2015). 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).

8 Conclusions

Innovations are key to enabling more sustainable agri-food systems but can come with sustainability synergies and trade-offs across the three pillars of sustainability. One such innovation that is on the rise in the Global South is agricultural mechanization. This review suggests that many—but not all—Asia and Latin America and the Caribbean countries have experienced considerable progress regarding mechanization more lately, driven by farming system evolution, structural transformation, and urbanization. In Sub-Saharan Africa, progress has been limited on average but farming systems have been rapidly evolving and mechanization has emerged as a top policy priority. Mechanization comes with many opportunities but also some risks for the sustainable transformation of agri-food systems in the Global South. This literature review suggests that agricultural mechanization can help to make agri-food systems more sustainable from a socio-economic perspective due to positive effects related to labor productivity, poverty reduction, food security, and health and well-being, among others. Possible sustainability trade-offs concern biodiversity loss from farmland expansion and simplification, soil compaction and erosion and social aspects related to disparities between large and small farms, and women's disempowerment, among others. These trade-offs have to be taken seriously but can be greatly minimized or avoided with accompanying policies and investments. However, more efforts are needed to implement such solutions at scale and ensure that mechanization contributes to agri-food systems that respect all pillars of sustainability.

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