Experimental Agriculture (2023), vol. 59, e12, 1–27
doi:10.1017/S0014479723000091

RESEARCH ARTICLE

Animal traction, two-wheel tractors, or four-wheel tractors? A best-fit approach to guide farm mechanization in Africa

Thomas Daum, Anna Seidel, Bisrat G. Awoke and Regina Birner

Department of Social and Institutional Change in Agricultural Development, Hans-Ruthenberg-Institute of Agricultural Sciences in the Tropics, University of Hohenheim, Stuttgart, Germany
Corresponding author: Thomas Daum; Email: thomas.daum@uni-hohenheim.de

(Received 13 September 2022; revised 17 January 2023; accepted 21 June 2023)

Summary

Farm mechanization promises to help raise labor productivity and reduce the heavy toil of farming on the world's millions of smallholder farms, hence contributing to socioeconomic development in the Global South, in particular in Africa. While mechanization is therefore high on the African development agenda, there are heavy – at times dogmatic – debates on which technological pathway toward farm mechanization – animal traction, two-wheel tractors, and four-wheel tractors – should be supported by African governments and development partners. One discussion area relates to the future of animal traction. Proponents see a continued scope for the use of draught animals, whereas opponents see animal traction as old-fashioned and see a potential to leapfrog this mechanization stage. There are also debates on the potential of two-wheel tractors, with proponents arguing that such walk-behind tractors are more affordable and suitable for smallholder farmers, and opponents believing that such tractors lack efficiency and power and still come with a high drudgery. This paper argues that there are no blueprint answers on which technological pathway is 'best' but only answers on which one 'best fits' the respective conditions. Based on this premise, this paper introduces a 'best-fit' framework that allows for assessing the comparative advantages and disadvantages of the three technological pathways in different agroecological and socioeconomic conditions. The results suggest that all three forms of mechanization are associated with areas where they 'best fit'. All three farm mechanization pathways hinge on public policies and investments to create an enabling environment for private markets, as, ultimately, innovation processes should be market driven. The 'best-fit' framework enables governments and development partners to focus efforts to support farm mechanization on solutions that 'best fit' their country's farming systems and not on those that are politically most attractive, thereby contributing to sustainable agricultural mechanization and development.

Keywords: Agricultural mechanization; Animal traction; Draught animals; Farm mechanization; Four-wheel tractors; Two-wheel tractors

Introduction

Manual labor preoccupies much of the physical and intellectual resources of a large share of the world's 550 million family farms, in particular in the Global South (Daum, 2023; Lowder *et al.*, 2021, Van Vliet *et al.*, 2015). Despite hard work, many of these farms are associated with limited labor productivity, and consequently, high shares of poverty and hunger (Daum, 2023; Fuglie *et al.*, 2019). Moreover, the heavy toil of farming can undermine farm families' health and well-being (Daum and Birner, 2021; Ogwuike *et al.*, 2014), an aspect that will be exaggerated with the unfolding climate crisis (Dasgupta *et al.*, 2021). Importantly, the burden of manual agriculture is mainly shouldered by unpaid family work, in particular by women and children (André *et al.*, 2021; Daum, 2023). The International Labor Organization estimates that 70% of all child labor is taking place on farms, affecting 112 million children (ILO, 2021). This is heavily undermining their possibility to play and go to school (André *et al.*, 2021; Daum *et al.*, 2021). For adults, the high amount of time that has to be dedicated to manual work can undermine the pursuit of off-farm work, childcare activities, and food preparation (Johnston *et al.*, 2018), affecting various aspects that are important for human development such as education and nutrition. Increasing labor productivity and reducing the burden of labor can hence largely contribute to socioeconomic development in the Global South.

Against this background, governments and development partners across Africa have started to heavily promote farm mechanization to replace hoe and cutlass types of farming (Daum and Birner, 2020; FAO & AUC, 2018), which is the common mode of farming on 80% of all farms (FAO & AUC, 2018). Farm mechanization refers to the substitution of human power with animal and mechanical power in the fields of farmers and hence has a more narrow scope than agricultural mechanization, which covers the entire agricultural value chain (Daum and Kirui, 2021; FAO & AUC, 2018). The mechanization of land preparation is typically the first step of farm mechanization, making necessary the use of solutions that can pull equipment such as plows, harrows, and rippers (Binswanger, 1986). The renewed efforts of governments and development partners to promote farm mechanization are backed up by evidence highlighting how labor constraints increasingly undermine both agricultural land and labor productivity (Baudron *et al.*, 2015, 2019; Diao *et al.*, 2014; Silva *et al.*, 2019; Sims and Kienzle, 2006) and how mechanized farmers can successfully raise land and labor productivity and, consequently, improve various aspects of their livelihoods (e.g. Adu-Baffour *et al.*, 2019; Kirui, 2019; Mano *et al.*, 2020). Diao *et al.* (2020) have argued that African mechanization is increasingly held back not by a lack of demand but by supply-side constraints.

There are three major technological pathways toward farm mechanization: (1) the use of animal traction, (2) the use of two-wheel tractors, and (3) the use of four-wheel tractors. In all cases, farmers may own the respective technology or access the technology via asset-sharing arrangements (e.g. service provider models, cooperative ownership models). The history of farm mechanization shows that countries across the world have followed the three pathways to different degrees at different points in time. In Europe and North America, animal traction played a large role before the adoption of four-wheel tractors, and for a period, farmers combined both technologies (e.g. using tractors for plowing and draught animals for harrowing) (Daum *et al.*, 2018). Two-wheel tractors constituted entry points toward motorized mechanization for small farms in parts of Europe (Herrmann, 1994). In Asia, animal traction has equally played a large role, which has facilitated the rapid rise of tractors more recently (Diao *et al.*, 2020; Lawrence and Pearson, 2002), including two-wheel tractors in wetland rice production, and small horsepower four-wheel tractors in other farming systems (Diao et al, 2020; Pingali, 2007).

With Africa being at a mechanization crossroads where many countries already do or are considering whether to invest in mechanization technologies and supportive environments, as discussed above, there are heavy – at times dogmatic – debates about which of these technological pathways should be pursued (Daum and Birner, 2020; Daum et al, 2022; Mrema *et al.*, 2008). One discussion area relates to the future of animal traction. Proponents see a continued scope for the use of draught animals such as oxen and donkeys, either as a goal in itself or as an essential stepping stone toward motorized mechanization (Pingali *et al.*, 1987; Sims and Kienzle, 2006), whereas opponents argue that Africa can leapfrog the animal traction stage and directly focus on the use of tractors (FAO & AUC, 2018), as further deliberated below. The latter view is shared by many African governments who heavily focus on tractorization to 'modernize' agriculture (Cabral, 2022; Cabral and Amanor, 2022; Mrema *et al.*, 2008). In contrast, animal traction is often

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

seen as 'archaic and antiquated' (Wilson, 2003, p. 21) and has mostly been neglected by governments – except for a short period during the 1980s and early 1990s (Daum and Birner, 2020; Daum *et al.*, 2022; Mrema *et al.*, 2008; Pingali *et al.*, 1987). Another discussion area relates to the potential of two-wheel tractors, with proponents arguing that such single-axle tractors are more affordable and suitable for smallholder farmers (Baudron *et al.*, 2015; Kahan *et al.*, 2018), among other benefits, and opponents believing that such walk-behind tractors[1] are not efficient and have a limited potential to reduce the drudgery of farming (as discussed in Daum and Birner, 2020), among other disadvantages, as further discussed below.

The comparative advantages of the three technological pathways depend not only on the technologies themselves but also on the respective agroecological and socioeconomic contexts (see also Kahan *et al.*, 2018; Mrema *et al.*, 2008; Sims and Kienzle, 2006). Hence, there cannot be blueprint answers on which technological pathway is 'best' but only answers on which one 'best fits' the respective conditions. Farmers can best decide which technology 'best fits' their farms. However, while there are good reasons to leave the innovation process mostly to market forces, innovation processes do not take place in an institutional vacuum but are shaped significantly by the agricultural innovation system (Spielman and Birner, 2008; World Bank, 2012). This enabling environment includes the agricultural research and education system and accompanying science and technology and agricultural policies and investments (Spielman and Birner, 2008; World Bank, 2012).

The agricultural innovation system plays a strong role in the support of farm mechanization and can shape technological trajectories (Daum and Birner, 2017; Daum *et al.*, 2018; Diao *et al.*, 2020; FAO & AUC, 2018; Kahan *et al.*, 2018). For example, the comparative advantage of animal traction depends on public research (e.g. breeding programs on disease-tolerant draught animals), veterinary services (e.g. vaccination and deworming programs), and extension services, among others (Ellis-Jones *et al.*, 2005; Pearson and Vall, 1998). The relative advantage of tractors also hinges on public policies and investments, for example, related to knowledge and skills development for tractor owners, operators, and technicians (Daum and Birner, 2017; Daum *et al.*, 2018; Diao *et al.*, 2020; FAO & AUC, 2018; Mrema *et al.*, 2008). Past efforts by governments and development partners related to farm mechanization have often been misguided, leading to 'large amounts of equipment that is not suited to the specific SSA circumstances' and a 'graveyard of junked machinery' (Sims and Kienzle, 2006, p. 58) – an error that could be avoided with a better alignment of farm mechanization efforts with agroecological and socioeconomic requirements (Sims and Kienzle, 2006).

Against this background, this paper present a conceptual framework that can help governments and development partners to solve this 'best fit' challenge and better understand which technological pathways should be promoted with accompanying institutions and investments given the existing agroecological and socioeconomic conditions of their countries' farming systems. As argued by Mrema *et al.* (2008), 'a sound comprehension of the field situation and the priority operations to mechanize' is key for the success of farm mechanization, including an understanding of what 'level of mechanization should be applied' and what are 'the most appropriate way of promoting mechanization' (p. 35).

This paper proceeds as follows. In the 'Farm mechanization landscape in Africa' section, the authors present an overview of the agricultural mechanization landscape in Africa, that is, the history and status of animal traction, two-wheel tractors, and four-wheel tractors. In the 'Debates

[1]There are pure walk-behind tractors without a seat but also ride-on two-wheel tractors with a seat for the operator. In this case, the tractors typically have a third small wheel. The seat and wheel are usually removable and may be taken off for certain operations where they are not needed or where they may get in the way. In paddy rice cultivation in moist, muddy soils, common in South-East Asia, seats can be used during most operations. Seats may also be used during transporting. In dryland agriculture and on hard-to-work soils such as vertisols, seats typically have to be removed, as the operator needs to walk alongside the tractor to better guide it and to apply additional force and as the tractor may lose traction in the front when the operator is seated due to the operator's load.

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

Table 1. Status of farm mechanization in Africa

		Human power	Animal power	Mechanical power§	Source
All Africa		≈80%	≈15%	≈5%	FAO & AUC (2018)
North Africa	Egypt		≈4%	≈57%	Kirui (2019)
East	Ethiopia		≈55%–80%	≈1–5%	Berhane *et al.* (2020); Kirui (2019); Sheahan and Barrett (2017)
	Kenya		≈17%	≈13%	Kirui (2019)
	Tanzania		≈25%	≈5–14%	Mrema *et al.* (2020); Sheahan and Barrett (2017)
	Uganda			<1%	Sheahan and Barrett (2017)
West	Burkina Faso		≈69%	≈1%	Kirui (2019)
	Ghana		≈5%	≈12–33%	Diao *et al.* (2020); Kirui (2019)
	Niger		≈42%	<1%	Kirui (2019); Sheahan and Barrett (2017)
	Nigeria		≈25%	≈2–7%	Sheahan and Barrett (2017); Takeshima and Lawal (2020)
	Senegal		≈25%	<1%	Kirui (2019)
Central	Cameroon		<1%	<1%	Kirui (2019)
Southern	Malawi			<1%	Sheahan and Barrett (2017)
	Mozambique		≈10%	≈1%	Cabral (2022)
	South Africa		≈4%	≈70%	Kirui (2019)
	Zambia		≈10%	≈7%	Kirui (2019)
	Zimbabwe		≈65%	≈1%	Kirui (2019)

Notes: §*This includes two-wheel and four-wheel tractors, which are usually not separately assessed.*

on the future of African farm mechanization' section, the authors present some of the key debates on the advantages and disadvantages of animal traction, two-wheel tractors, and four-wheel tractors. In 'Best-fit framework to guide farm mechanization' section, the authors present and apply the conceptual 'best-fit' framework, which can help to guide policymakers and development partners investing in farm mechanization. The 'Discussion and policy implications' section discusses and concludes the paper.

Farm mechanization landscape in Africa

In Africa, most farming is still done with the help of hand tools such as hoes and cutlasses (FAO & AUC, 2018). FAO & AUC (2018) present estimates showing that around 80% of the farmland area in Africa is cultivated with human power and hand tools, animal power is used for 15% of the farmland area, and mechanical power (two-wheel and four-wheel tractors) on 5% of the farmland area. Table 1 provides some additional insights based on statistics from individual countries. In the following sections, trends related to each of the three technological pathways will be shown (see 'Animal traction'; 'Four-wheel tractors'; and 'Two-wheel tractors' sections).

Animal traction

The use of animal traction varies widely across the continent (see also Table 1). Northern Africa has a long tradition in the use of draught animals, potentially facilitating today's rapid adoption of tractors (Starkey, 2000). In the Horn of Africa, for example, in Ethiopia and Eritrea, the animal-drawn *Maresha* plow is used for around 3000 years (Gebregziabher *et al.*, 2006; Starkey, 2000; Takele and Selassie, 2018), and animal traction continues to be widespread (see Table 1). There were large efforts to promote animal traction in various other African countries during colonialization (Starkey, 2000). Such efforts were revived in post-colonial Africa in the 1980s and 1990s, often driven by development partners, following the failure of state-led tractorization programs and the fossil fuel crisis (Mrema *et al.*, 2008; Starkey, 2000; Wilson, 2003).

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

Efforts to promote draught animals were successful in some Western African countries (e.g. Burkina Faso, Niger) and Southern African countries (e.g. Zambia, Zimbabwe, and Malawi) but failed in other regions, in particular where farmers were still practicing forest and bush fallow systems at the time (Ehui and Polson, 1993; Havard *et al.*, 2000; Starkey, 2000). Adoption rates are close to zero in much of Central Africa due to animal diseases (Alsan, 2015; Mrema *et al.*, 2008; Pingali *et al.*, 1987). While animal traction is on the rise in some parts of Africa (Diao *et al.*, 2020; Sims and Kienzle, 2006), it has stagnated or declined in other parts, in particular in Eastern and Southern Africa (Baudron *et al.*, 2015; Mrema *et al.*, 2008).

The most common types of draught animals are cattle (i.e. oxen or bullocks), but donkeys, mules, buffalos, and even camels are also used (Ellis-Jones *et al.*, 2005; Starkey, 2000). Donkeys were long considered only strong enough for transportation but are increasingly used for cultivation as climate change necessitates the use of more drought-resilience animals (Ellis-Jones *et al.*, 2005; Starkey, 2000). Draught animals are used for farm cultivation (i.e. land preparation, and weeding), water-lifting, milling, threshing, and transportation, among other activities (Ellis-Jones *et al.*, 2005; Sims and Kienzle, 2006; Starkey, 2000).

Four-wheel tractors

Across Africa, 5% of the farmland is cultivated using tractors, with higher adoption rates in Northern Africa and South Africa and lower adoption rates in Sub-Saharan Africa (FAO & AUC, 2018). Tractors were historically only used on large commercial farms, often a legacy of colonial times, and as part of state-supported mechanization projects, many of which collapsed due to governance challenges (Daum and Birner, 2017; FAO & AUC, 2018; Mrema *et al.*, 2008; Pingali, 2007; Pingali *et al.*, 1987). More recently, some African governments again set up public mechanization programs, but there are again signs of failure (Daum and Birner, 2017; Diao *et al.*, 2014; FAO & AUC, 2018). Farming system evolution and rising rural wages have led to vibrant private markets for new and secondhand tractors in some countries such as Ghana and Kenya (Daum and Birner, 2020; Diao *et al.*, 2020; FAO & AUC, 2018) but in other countries, the use of tractors is 'extremely low' (Mrema *et al.*, 2008) (see also Table 1). Tractor use rates vary widely not only across but also within countries. For example, in Ghana, it ranges from 2% in the forest zone to 88% in the savannah zone (Diao *et al.*, 2020).

Two-wheel tractors

Two-wheel tractors only play a role in some countries and farming systems. After the failure of state-led mechanization projects to promote the use of four-wheel tractors in the 1960s and 1970s, government and development partners shifted attention toward what was then considered 'appropriate' machinery in the form of animal traction as well as mini-tractors and two-wheel tractors (Mrema *et al.*, 2008). As pointed out by Mrema *et al.* (2008) such two-wheel tractors were supported with heavy investments but 'were nevertheless rejected by farmers throughout Africa' (p. 22), partly because, just like with many efforts to promote animal traction and four-wheel tractors, there was a lack of economic demand at the time.

Today, manufacturers in particular from Asia are trying to supply two-wheel tractors[2] across much of Africa but significant adoption has taken place in only a few countries – that is, Madagascar, Tanzania, and South Africa – and mostly in rice-based irrigated farming systems (Mrema *et al.*, 2018). In Tanzania, the number of two-wheel tractors rose from 300 to 9000 between 2005 and 2015 – for comparison, there are around 13 000 four-wheel tractors (Mrema

[2]These are versatile two-wheel tractors that can be used to pull several attachments such as ploughs, planters, spreaders, sprayers, reapers, and trailers, and power stationary equipment such as threshers, shellers, and pumps. Hence, they are not to be mixed up with rice transplanters.

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

et al., 2020). This was driven by the government importing large numbers of two-wheel tractors as well as a prolonged drought that killed 50% of the draught oxen (Mrema *et al.*, 2020). In Ethiopia, there are around 4000 two-wheel tractors (Baudron *et al.*, 2015), of which three-quarters were publicly procured (Kahan *et al.*, 2018). Data from one of Ethiopia's largest agricultural machinery dealer reveal that its share of two-wheel and small tractors was 12% in 2015/2016 (Berhane *et al.*, 2020).

Overall, the import value of two-wheel tractors as compared to four-wheel tractors is marginal in Ethiopia (Berhane *et al.*, 2020); however, adoption is gaining momentum as they were promoted as part of the Farm Mechanization and Conservation Agriculture for Sustainable Intensification (FACASI) project between 2013 and 2019 (FACASI, 2019).[3] In Nigeria, one of the largest markets for farm mechanization, two-wheel tractors play only a very limited role (Takeshima and Lawal, 2020). In Kenya, another large mechanization market, only around 500 two-wheel tractors were in operation in the last decade, mostly in horticultural production (Kahan *et al.*, 2018).

Debates on the future of African farm mechanization

Farm mechanization is often understood as a process along three stages: (1) human power, (2) animal power, and (3) mechanical power. Figure 1 depicts two major discussions challenging this 'mechanization ladder' view. First, there are debates on whether animal traction is a necessary rung or can be leap-frogged. Second, there are debates on the appropriate scale of motorized farm mechanization or – formulated simplistically – how many wheels tractors need to have. This debate is related to the question of whether two-wheel tractors present an alternative rung for smallholder mechanization, either as a goal in itself or as an intermediate step toward the use of four-wheel tractors.[4] Figure 1 shows these different technological trajectories. Each of these debates will be presented in detail in the next sections.

The future of animal traction

The future role of animal traction is heavily debated. Many policymakers, development partners, researchers, and also farmers nowadays believe that animal traction is old-fashioned and can be 'leapfrogged' (Ellis-Jones *et al.*, 2005; FAO & AUC, 2018; Mrema *et al.*, 2020; Wilson, 2003). Tractors are seen as a symbol of modern agriculture, whereas animal traction, albeit progress from hoe and cutlass farming, is seen as associated with lower efficiency, higher labor use, and drudgery. Scientific evidence confirms the higher efficiency and speed and hence the gain in timeliness associated with tractors vis-à-vis animal traction as well as the lower labor use and drudgery as compared to animal traction (Sims and Kienzle, 2006). Sims and Kienzle (2006) show that animal traction can reduce the workload associated with manual land preparation from around 500 hours to around 60 hours per hectare – however, tractors need only a few hours. In addition, animal traction requires significant labor use for producing fodder, fetching water, herding, and tending the draught animals outside of the farming season (Ehui and Polson, 1993; Mrema *et al.*, 2008; Sims and Kienzle, 2006; Wilson, 2003), when they are a "drain on resources whilst performing no useful production function" (Wilson, 2003, p. 26). According to some estimates, oxen, for example, are unused most of the time and only 15% of the feed intake is used for 'production'

[3]https://www.cimmyt.org/projects/farm-mechanization-and-conservation-agriculture-for-sustainable-intensification-facasi/

[4]There are several examples of farming systems where farmers first adopted animal traction, then two-wheel tractors, and eventually four-wheel tractors such as Japan (Hegazy *et al.*, 2013) and South Korea (Yun and Kim, 2013). There are also signs of this happening in Myanmar (Win *et al.*, 2020). Also in some parts of Europe (e.g. Southern Germany, Switzerland, Italy, and some Eastern European countries), two-wheel tractors were an entry point into mechanization for smallholder farmers but they later also adopted four-wheel tractors (Herrmann, 1994).

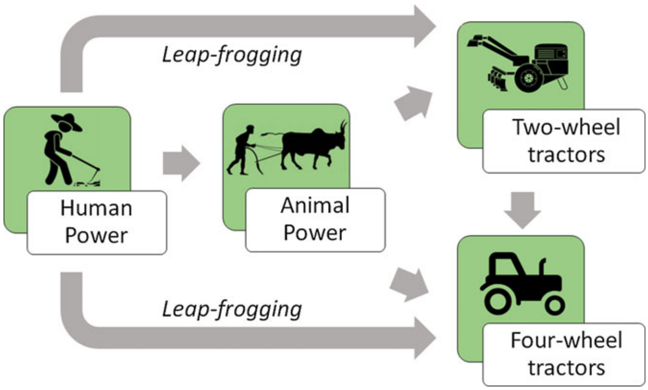

Figure 1. Technological pathways in farm mechanization.
Source: Authors.

(Tefera, 2011; Wilson, 2003). Moreover, unlike tractors, draught animals need a substantial period to physically mature and to be trained – often around 4 years – before they can be used to work in the fields and then the working life is relatively short (Wilson, 2003).

Proponents of tractorization also argue that tractors are becoming more adapted to African farming systems as well as less expensive, largely due to growing competition in global manufacturing markets from countries such as Brazil, China, and India (FAO & AUC, 2018). At the same time, the costs of purchasing and maintaining draught animals are rising with population growth, farming system evolution, and climate change, which put pressure on pastures and land for fodder production (Baudron *et al.*, 2015; Kahan *et al.*, 2018; Mrema *et al.*, 2020). In Ethiopia, a pair of draught oxen need around nine tons of forage annually, and this is increasingly difficult to ensure (Takele and Selassie, 2018). Baudron *et al.* (2015) therefore argue that ensuring sufficient farm power supply increasingly requires motorized solutions. In various Northern African countries, tractors are now replacing draught animals as farmers see 'little economic justification for maintaining oxen that walk quite slowly and are relatively expensive to own' (Starkey, 2000). The same is happing in some Eastern African and Southern African countries (Mrema *et al.*, 2008, 2020). Opponents of animal traction also raise animal health and welfare concerns, as animals are frequently exposed to heat, water, nutrition, and work stress, and may be badly handled and treated (Ellis-Jones *et al.*, 2005; Ramaswamy, 1998; Wilson, 2003). Some of the challenges will increase with climate change (Baudron *et al.*, 2015; Kahan *et al.*, 2018; Mrema *et al.*, 2020).

There are also policymakers, development partners, and researchers who argue that there is continued scope for animal traction in parts of Africa (Daum *et al.*, 2022; Houssou *et al.*, 2013; Thierfelder, 2021). While draught animals are less powerful than tractors, animal traction also helps to reduce labor requirements and overcome labor bottlenecks, enabling higher crop yields and areas expansion in many areas (Ehui and Polson, 1993; Ellis-Jones *et al.*, 2005; Pearson and Vall, 1998; Sims and Kienzle, 2006; Wilson, 2003). For the majority of African smallholder farmers, using animal draught power would already mean progress. Animal traction is argued to be more affordable and suitable for smallholder farmers (Ellis-Jones *et al.*, 2005; Pearson and Vall, 1998; Pingali *et al.*, 1987; Starkey, 2000; Takele and Selassie, 2018; Tefera, 2011). This argument is supported by Ellis-Jones *et al.* (2005) who show that animal traction 'is usually less costly than both tractors and hand labor' (p. 286). Sims and Kienzle (2006) argue that the 'efficient application of draught animal power (. . .) provides the best immediate strategy for reducing the problem of farm power shortage in SSA' (p. xiii). Baudron *et al.* (2015) argue that 'improved mechanization based on animal traction is probably the most viable option to increase the power supply in many

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

parts of ESA [Eastern and Southern Africa] where draught animals represent the main source of power' (p. 892–893). Another argument for animal traction is that it is more 'green' as it requires no fossil fuel (Cerutti *et al.*, 2014; Mrema *et al.*, 2008) and foreign currency (Melaku, 2011); however, this neglects that some draughts animals cause substantial methane emissions and other emissions can result from the cultivation of fodder crops and degradation of land and vegetation due to heavy grazing (O'Mara, 2011; Wilson, 2003). Animal traction sets are also more lightweight, reducing soil compaction risks (Takele and Selassie, 2018).

Owning draught animals as compared to hiring tractors may come with additional advantages for farmers. Farmers can use the animals for transportation, pumping water, and running mills, among others, and can use them as sources of meat, milk, hide, manure, and biogas (Ellis-Jones *et al.*, 2005; Pearson and Vall, 1998; Tefera, 2011; Wilson, 2003). Some of the aspects can allow farm households to generate additional income. Proponents of animal traction often believe in the great potential of crop-livestock integration to raise land and labor productivity, improve food and nutrition security, and reduce poverty, in particular for farmers practicing subsistence or near subsistence farming (Wilson, 2003). Another advantage is related to the possibility to use livestock as a financial saving mechanism (to store wealth in animals and use them to build capital) and for risk management in the absence of formal finance and insurance markets (Jahnke, 1982 and Upton, 2004). Pingali *et al.* (1987) argued that bypassing the animal traction is difficult as tractors are more likely to be adopted where farmers are already familiar with the plow and just need to substitute animals with tractors. Confirming this, Diao *et al.* (2020) found that in Asian countries the spread of tractors and the emergence of tractor service markets was facilitated by the familiarity with draught animals and the existence of animal traction service markets. Livestock can also have a range of other social and cultural functions (Jahnke, 1982). Owning draught animals rather than relying on tractor service markets may be associated with more prestige and may enhance autonomy as farmers owning draught animals do not need to compete with other farmers for tractors, which can translate to large yield penalties when tractors serve farmers too late or not at all (see, e.g., Daum, 2023). Importantly, some marginalized sub-populations may value self-reliance more highly than the general population.

How many wheels do tractors need?

Some scholars associate high hopes with two-wheel tractors for African farm mechanization. This is partly due to the key role of two-wheel tractors during farm mechanization in parts of Asia, where they were one key element to allow smallholder farmers to become mechanized and hence minimize the mechanization divide (Bhattarai *et al.*, 2020; Diao *et al.*, 2020, Justice and Biggs, 2020; Win *et al.*, 2020). Two-wheel tractors are argued to be more adapted to and more efficient on small plots compared to four-wheel tractors (Baudron *et al.*, 2015; Kahan *et al.*, 2018; Van Loon *et al.*, 2020). Two-wheel tractors are often embraced under the concept of scale-appropriated machinery, where 'machines are adapted to farm size and not the opposite' (p. 154), which reduces the need for land consolidation that is argued to be associated with the use of four-wheel tractors (Baudron *et al.* 2019b). Two-wheel tractors are also argued to be better able to maneuver around traditional landscape features such as trees and tree stumps (Baudron *et al.* 2015, 2019b; Kahan *et al.*, 2018; Van Loon *et al.*, 2020), hence being better able to preserve farm diversity and biodiversity-friendly mosaic type of landscapes (Baudron *et al.*, 2015; Daum *et al.*, 2020, 2022). Two-wheel tractors are also said to reduce soil compaction risks given their lower weight (Baudron *et al.*, 2015; Van Loon *et al.*, 2020).

Two-wheel tractors are typically significantly less expensive, making them easier to finance, which is a large promise given the challenges associated with mechanization finance (Baudron *et al.*, 2015; Daum and Birner, 2020; Kahan *et al.*, 2018; Van Loon *et al.*, 2020). Two-wheel tractors are also said to be easier to operate, maintain, and repair (Baudron *et al.*, 2015; Kahan *et al.*, 2018; Van Loon *et al.*, 2020). In Tanzania, for example, local motorcycle dealers and mechanics also

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

offer spare parts and repair services for two-wheel tractors due to their simple single-cylinder engine – whereas owners of four-wheel tractors have to travel larger distances to find skilled mechanics and spare parts (Mrema *et al.*, 2020). Two-wheel tractors can fulfill various functions: from cultivation to threshing, shelling, water pumping, and transport (Diao *et al.*, 2014; FACASI, 2019; Kahan *et al.*, 2018).

There are also critical voices about two-wheel tractors. Many stakeholders argue for the use of four-wheel tractors as they are faster and more efficient and hence improve timeliness and are more energy- and labor-saving than two-wheel tractors (Baudron *et al.*, 2015; Daum and Birner, 2017). Moreover, four-wheel tractors are argued to have an advantage over two-wheel tractors as the latter is still associated with heavy physical work – often under hot conditions and in direct sunlight without shade (Daum and Birner, 2020). It has also been shown that two-wheel tractors can lack sufficient farm power to work under rain-fed heavy soil conditions (Daum and Birner, 2020). Baudron *et al.* (2015) have argued that it is 'well known that 2WTs can only produce enough traction to plow wet paddy fields, but not dry soils in rainfed conditions' (p. 894).

There are also discussions on how large four-wheel tractors have to be. Diao *et al.* (2020) argue that parts of Africa face more soil workability constraints as compared to Asia; hence, there is a rationale for larger and more powerful tractors in such areas. However, in many other areas in Africa, tractors are argued to be too large and overpowered (Diao *et al.*, 2020). This is problematic because larger tractors are more expensive and require higher utilization rates to be profitable and can also trigger land consolidation, the removal of farm trees, and lead to soil compaction (Daum, 2023; Diao *et al.*, 2020). Thus, there is a rationale to strike a 'balance between size and efficiency' (Diao *et al.*, 2020). Such tractors are just large enough to be sufficiently powerful to work on local soil conditions but as small as possible to reduce economic and environmental trade-offs.

Best-fit framework to guide farm mechanization

Table 2 shows a conceptual framework to better understand which of the three technological pathways (animal traction, two-wheel tractors, and four-wheel tractors) 'best fits' under different conditions. The framework focuses on the 'best fit' for farm production activities such as land preparation. The framework is based on the understanding that the comparative advantage of the three technological pathways depends on agroecological and socioeconomic factors (termed layers in Table 2). Each of these layers comprises a set of different dimensions (e.g. farming system evolution, agroecological zones, soil texture), which can have different characteristics (e.g. light and heavy in the case of soil texture). The characteristics associated with the dimensions are mostly fixed (e.g. agroecological zones or topography), but some can be changed (e.g. trees, stumps, and stones can be removed and animal diseases can be eradicated). For simplicity, only the extreme expressions of the characteristics are shown, but these are just the ends of continuums. Institutional factors also impact the comparative advantage of each of the three technological pathways, as argued above; however, they are exogenous and hence not shown as part of the 'best-fit' framework. Institutional factors can be shaped by policy action, which should be guided by the 'best-fit' framework. It is important to point out that some combinations of characteristics are impossible or unlikely in reality. Moreover, the characteristics of some dimensions can have 'knock-out' characters. For example, a high prevalence of specific animal diseases completely rules out the use of animal traction even where animal traction enjoys a comparative advantage related to most other dimensions. Such 'knock-out'-parameters make the scoring of dimensions and characteristics difficult.

Table 3 shows the comparative advantages and disadvantages of the three technological pathways (animal traction, two-wheel tractors, and four-wheel tractors) across all agroecological and socioeconomic dimensions, which allows assessing which of the three technology options 'best fits' the respective characteristics. In Table 3, comparative advantages are marked in dark

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

Table 2. Agroecological and socioeconomic dimensions affecting farm mechanization

Layers	Dimension	Characteristics			
Agroecological	Farming system evolution	*Forest fallow*	*Bush fallow*	*Grass fallow*	*Annual cultivation*
	Agroecological zones	*Arid*	*Semi-arid*	*Semi-humid*	*Humid*
	Soil texture	*Light*		*Heavy*	
	Production type	*Dryland*		*Surface irrigation*	
	Topology	*Flat*		*Hilly*	
	Tree cover	*Low*		*High*	
	Stumps and stones	*Low*		*High*	
	Mixed farming (crop-livestock)	*No*		*Yes*	
	Pasture, fodder, water availability	*Low*		*High*	
	Animal disease prevalence	*Low*		*High*	
	Heat and humidity stress	*Low*		*High*	
Socioeconomic	Farm sizes	*Small*		*Large*	
	Labor costs	*Low*		*High*	
	Energy costs	*Low*		*High*	

Source: Authors.

Table 3. Best-fit framework to guide farm mechanization

Layers	Dimensions		Human power	Animal traction	Two-wheel tractors	Four-wheel tractors
Agroecological	Farming system evolution	Forest fallow	++	––	––	––
		Bush fallow	++	––	––	––
		Grass fallow		++		
		Annual cultivation			++	++
	Agroecological zone	Arid	++	––	++	
		Semi-arid				
		Semi-humid				
		Humid	++	––		
	Soil texture	Light		++	++	
		Heavy	––	––	––	++
	Production type	Dryland				
		Surface Irrigation		++	++	––
	Topology	Flat				
		Hilly		++	++	––
	Tree cover	Low				
		High	++	++	++	––
	Stumps and stones	Low				
		High	++	++	––	––
	Mixed farming (crop-livestock)	No				
		Yes		++		
	Pasture, fodder, water availability	Low		––	++	++
		High				
	Animal disease prevalence	Low				
		High		––		
	Heat and humidity stress	Low				
		High	––	––	––	++
Socioeconomic	Farm sizes	Small	++	++	++	––
		Large	––			++
	Labor costs	Low				
		High	––		++	++
	Energy costs	Low				
		High	++	++	––	––

Source: Authors. Note: ++ (Dark Green) = Comparative Advantage; Empty (Light Green) = Neutral; –– (Yellow) = Comparative Disadvantage green and comparative disadvantages are marked in yellow. Light green colors signal that the technologies have no clear advantages or disadvantages. A broad-brush analysis suggests that animal traction has potential in areas with small and fragmented farm holdings in semi-arid and semi-humid agroecological zones with light soils as long there is sufficient pasture and water available (see Table 3). Two-wheel tractors also have a comparative advantage where farms are small and fragmented (see Table 3). Two-wheel tractors have a comparative advantage over animal traction in arid and semi-arid agroecological zones, where there is a lack of sufficient pastures and water, where there is a high prevalence of animal diseases, and where labor availability is more limited (see Table 3). Four-wheel tractors have a comparative advantage where farms are large and not fragmented – or where asset-sharing arrangements can be set up easily – and under rainfed conditions on more heavy soils (see Table 3).

In the subsection sections, five major mechanization patterns in the Global South will be explained with the help of the framework to better illustrate its explanatory power (see the 'Using the framework to explain major mechanization trajectories in Global South' section). Afterward, the comparative advantages and disadvantages of the three technological options concerning all agroecological and socioeconomic dimensions are discussed in more detail based on the available empirical evidence (see the 'Comparative advantages and disadvantages of mechanization solutions for all dimensions' section).

Using the framework to explain major mechanization trajectories in Global South

There is a wide range of different mechanization trajectories during which farmers adopt (or do not adopt) different mechanization solutions (see Fig. 1). Three of the trajectories end up in the use of four-wheel tractors:

(1) Hand power → animal traction → two-wheel tractors → four-wheel tractors
(2) Hand power → animal traction → four-wheel tractors
(3) Hand power → four-wheel tractors

In two trajectories, the use of two-wheel tractors is the outcome:

(4) Hand power → animal traction → two-wheel tractors
(5) Hand power → two-wheel tractors

One trajectory each results in the use of animal traction or hand power:

(6) Hand power → animal power
(7) Hand power

In the following, we apply our framework to explain three typical and stylized mechanization trajectories in the Global South. Table 4 showcases in more detail how the framework can help to understand why the specific mechanization trajectories were observed:

(1) ***Four-wheel tractors in rainfed farming with heavy soils and animal diseases:*** These farming systems have typically witnessed a mechanization trajectory from hand power directly to four-wheel tractors. Rainfed farming systems with heavy, clayey soils such as vertisols are common across temperate and subtropical of the Global South. In Africa, vertisols, for example, are common in Cameroon, Chad, Ethiopia, Kenya, parts of South Africa, and Sudan (Jones *et al.*, 2013). As depicted in our framework, under such conditions, four-wheel tractors have a comparative advantage over two-wheel tractors, which typically lack sufficient power (see also the 'Soil texture' section). In areas that are

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

Table 4. Best-fit framework to understand three typical mechanization trajectories

Layers	Dimensions	Four-wheel tractors in rainfed farming with heavy soils and animal diseases 	Two-wheel tractors in wetland rice production 	Animal traction in hilly farming systems with stones 
Agroecological	Farming system evolution	Annual cultivation	Annual cultivation	Annual cultivation
	Agroecological zone	Arid, semi-arid, semi-humid, humid	Semi-humid, humid	Semi-arid, semi-humid
	Soil texture	Heavy	Heavy	Light–Heavy
	Production type	Dryland	Surface Irrigation	Dryland
	Topology	Flat	Flat, Hilly	Hilly
	Tree cover	Low	Low	Low
	Stumps and stones	Low	Low	High
	Mixed farming (crop-livestock)	No	No, Yes	Yes
	Pasture, fodder, water availability	Low	Low–High	High
	Animal disease prevalence	High	Low	Low
	Heat and humidity stress	High	High	Low
Socioeconomic	Farm sizes	Small–Large	Small	Small–Large
	Labor costs	High	High	Low
	Energy costs	Low	Low	High

Source: Authors.

characterized by both heavy soils and a high prevalence of animal diseases such as Cameroon and the southern parts of Chad and South Sudan, animal traction is very likely to be leap-frogged as the prevalence of animal diseases constitutes a ‘knock-out’-parameter, as previously discussed. Animal diseases are widespread in parts of Western Africa and Central Africa (see also ‘Animal disease prevalence’ section).

(2) ***Two-wheel tractors in wetland rice production:*** Production systems with surface irrigation typically witness a mechanization trajectory from hand power to animal traction – and with rising labor costs – to two-wheel tractors (Diao *et al.*, 2020; Pingali 2007). An example is wetland rice production in the Indo-Gangetic plains (i.e. India and Bangladesh) (Diao *et al.*, 2020; Pingali 2007). Based on our framework (see Table 3), the continued appeal of two-wheel tractors over four-wheel tractors in such systems is not surprising as heavy four-wheel tractors have a comparative disadvantage in such production systems as they can easily sink in and get stuck (Adamu *et al.*, 2014; see also the ‘Production type: Surface irrigation versus dryland’ section).[5] Moreover, less farm power is needed in such systems as compared to dryland systems, reducing the need for large tractors (Baudron *et al.*, 2015). In Asia, such systems are typically also characterized by small plots, another comparative advantage of two-wheel tractors (see also the ‘Farm sizes and fragmentation’ section). In brief, in such systems, two-wheel tractors face comparative advantages, in particular where plots are small; however, there can also be scope for small four-wheel tractors (see also Pingali *et al.*, 1987).

[5]It is worth pointing out that four-wheel tractors are more common in dryland production systems in Asia (Diao *et al.*, 2020; Pingali, 2007).

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

(3) ***Animal traction in hilly farming systems with stones:*** Hilly farming systems typically see a transition from hand power to animal traction. Examples are the Andean parts of South America, the East African highlands, and the Himalayan areas of Asia such as Nepal. As shown in our framework, four-wheel tractors have a clear disadvantage in such systems due to the risk of overturning (see also the 'Topography' section). While two-wheel tractors can be used in hilly areas in principle, they are ill-suited where there is also a high prevalence of stones. Many parts of the Ethiopian highlands are both hilly and stony, and hence animal traction continues to be appealing.

Comparative advantages and disadvantages of mechanization solutions for all dimensions

Farming system evolution

According to the theory of farming system evolution, the early stages of farming system evolution are characterized by shifting cultivation based on forest and bush fallow systems, which are typically associated with the use of manual labor. In an Africa-wide study, Pingali and Binswanger (1984) found that all sampled study sites practicing forest and bush fallow systems relied on the use of manual labor and hand hoes. In this stage of farming system evolution, the use of the plow is uneconomical, among other reasons, because of the high costs related to de-stumping and removing root networks (Ehui and Polson, 1993). Moreover, weed pressure tends to be low and farmers often use fire for clearing the land (Pingali *et al.*, 1987; Ruthenberg, 1980). Animal traction is usually not necessary and is undermined by a lack of grazing areas and animal diseases such as trypanosomiasis (Ehui and Polson, 1993; Havard and Le Thiec, 1999; Pingali *et al.*, 1987). The poor track record of public efforts to promote farm mechanization (incl. both animal traction and tractors) in the 1960s and 1970s is to a large degree attributable to the lack of farming system evolution at the time, which made it uneconomic for farmers to adopt such technologies (Ehui and Polson, 1993; Pingali *et al.*, 1987).

With increasing population growth and market demand, farmers shorten fallow periods and move from shifting cultivation (forest fallow, bush fallow) toward annual and later multiple cultivations (Boserup, 1965; Ruthenberg, 1980). This shift entails an intensification of farm production and comes with rising labor requirements per hectare of cultivated land (Ehui and Polson, 1993; Ruthenberg, 1980; Pingali and Binswanger, 1984; Pingali *et al.*, 1987). Forests and bushlands make a place for grassy lands, a change that comes with a reduced prevalence of some animal diseases and an opening up of the space for pastures (Ehui and Polson, 1993; Havard and Le Thiec, 1999; Pingali and Binswanger, 1984). At the same time, de-stumping costs decline (Ehui and Polson, 1993; Pingali *et al.*, 1987). All of this increases the appeal and comparative advantage of draught animals over hand tools – whereas tractors remain unattractive.

With continued population growth, there are growing pressures to convert grazing land to cropland, reducing the comparative advantage of draught animals (Pingali *et al.*, 1987; Ruthenberg, 1980). This is now happening, for example, in parts of Ethiopia where there is increasingly 'less communal land for grazing and raising livestock, especially in densely populated areas' (Takele and Selassie, 2018). Farmers may start to cultivate fodder crops, but this typically raises the costs of feeding animals and is very labor-intensive (Ehui and Polson, 1993). Moreover, taking aside land and labor for producing fodder crops can come with opportunity costs regarding the production of food or cash crops or pursuing alternative income-generating activities (Sims and Kienzle, 2006). Crops residues may also be used, but they are of lower nutritional value unless combined with supplements (Sims and Kienzle, 2006). Hence, with annual cultivation, there is a growing comparative advantage of switching to motorized mechanization (Pingali *et al.*, 1987; Ruthenberg, 1980), which can be two-wheel or four-wheel tractors.

Ruthenberg (1980) measured farming system evolution using so-called R-values. R-values are derived by dividing the harvested area by the agricultural land area and multiplying this value by 100. According to Ruthenberg (1980), animal traction typically evolves with R-values

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

above 33% and tractors evolve with R-value above 80%. In the past, efforts to promote both draught animals and motorized farm mechanization failed in parts of Africa due to the lack of farming system evolution at the time, as farmers were still practicing forest and bush fallow systems, which made it uneconomic for farmers to adopt such technologies (Ehui and Polson, 1993; Pingali *et al.*, 1987; Starkey, 2000). In the last decades, shifting cultivation is declining, and cropping intensities are increasing in all but a few countries (Heinimann *et al.*, 2017; Sebastian, 2014). This means that the farming systems in many parts of Africa have reached intensification levels surpassing Ruthenberg's R-value of 80%, which is typically associated with a shift toward the use of tractors (Diao *et al.*, 2020).

Heinimann *et al.* (2017) show a great map indicating where shifting cultivation was practiced during the 1960s and 1970s but where farmers now practice annual cropping. The map reveals that shifting cultivation was still practiced during the 2010s, in particular in large parts of Central Africa. In these areas, farmers may still use hand labor or else animal traction can have a comparative advantage over the use of tractors. Sebastian (2014) also provides a map showing that annual cultivation is now practiced in many parts of Africa; however, there are still also parts where extensive fallow periods are possible.

Agroecological zones

Agroecological zones and growing periods also shape the comparative advantage of the three technological pathways. In arid areas, growing periods typically do not exceed 90 days; in semi-arid areas, growing periods last between 90 and 180 days; in sub-humid areas, growing periods last 180–270 days; and in humid areas, the growing period can last longer than 270 days. Sebastian (2009) provides an graphical overview of agroecological zones in Africa.

In arid areas, farmers practicing rainfed agriculture have fewer days to complete land preparation as compared to more farmers in more humid tropical areas as tillage cannot start before rainfall has sufficiently increased soil moisture and reduced soil hardness (Pearson and Vall, 1998). In the arid area, farmers often refrain from using draught animals because their utilization rate remains limited and the costs of maintaining draught animals (including during the extended off-farm season) outweigh the benefits (Baudron *et al.* 2015; Mrema *et al.*, 2020; Pearson and Vall, 1998; Sims and Kienzle, 2006). In many arid parts of Africa, animals can be affected by heat stress and the provision of sufficient feed is also a challenge during the extended dry season (Ellis-Jones *et al.*, 2005). In such areas, draught animals are only used for transport and water lifting (Havard *et al.*, 2000).

At the same time, rental markets for tractors are also more difficult to set up in arid areas as farmers need services only within a short period to avoid yield penalties from delayed operations, giving a comparative advantage to solutions where farmers have more control themselves (Diao *et al.*, 2014; Mrema *et al.*, 2008; Pingali *et al.*, 1987) and that allows farmers to fully 'exploit the short rainy season' (Mrema *et al.*, 2008). With tractors being too expensive to own for most farmers and tractor service markets being difficult to set up, there appears to be a continued comparative advantage for using manual labor or else the use of more inexpensive two-wheel tractors, which appears to have a comparative advantage over animal tractions as they work more quickly and come with fewer off-season costs. Such a comparative advantage of two-wheel tractors has been observed for example in the more arid areas of Tanzania (Mrema *et al.*, 2020).

In semi-arid areas under rainfed agriculture, animal traction is affected by similar challenges as in arid areas as growing seasons are relatively short and grazing land suffers in the long dry season (Sims and Kienzle, 2006). Tractor service markets are also affected by similar synchronicity and seasonality problems (Mrema *et al.*, 2008; Sims and Kienzle, 2006). However, the challenges faced by animal traction and four-wheel tractors in semi-arid areas appear to be less pronounced as compared to arid areas as the growing seasons are longer and the access to forage improves compared to arid areas. In sub-humid areas, the challenges are even less pronounced. This

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

explains why animal traction is mostly concentrated in semi-arid and sub-humid areas of Africa (Havard *et al.*, 2000; Havard and Le Thiec, 1999; Pearson and Vall, 1998; Williams, 1997) – as well as in high-altitude regions (Havard and Le Thiec, 1999). Pingali *et al.* (1987) have argued that the 'high-rainfall, semiarid zone, and the subhumid zone are ideal for such integration of crops and livestock' (p. 109) and 'for intensive farming and draught power' (p. 122). Outside the Horn of Africa, the spatial concentration of animal traction is also a result of colonialization which introduced animal traction 'mostly in the moist savannah zone where pastoralists settled and began to grow cash crops such as groundnuts and cotton' (Mrema *et al.*, 2008, p. 21). Tractors are argued to be 'best suited to the moist savannah areas' (Mrema *et al.*, 2008, p. 28, referring to Pingali *et al.*, 1987). In Ghana, tractor use is as low as 2% in parts of the forest zone and as high as 88% in the savannah zone (Diao *et al.*, 2020).

In humid zones, most soils 'are not suited to intensive production of field crops and are therefore inappropriate for use of the plow' (Pingali *et al.*, 1987, p. 173). Such soils are better suited for perennial and tree crops, whereas farm mechanization options (e.g. land preparation) are less needed and more limited (Pingali *et al.*, 1987). In many parts of the humid zones, farmers, therefore, practice 'permanent or semi-permanent systems of multi-story cropping', where human labor has an advantage (Sims and Kienzle, 2006). There is some scope for using tree-less cropping systems but only when Conservation Agriculture is practiced can land degradation be prevented (Pingali *et al.*, 1987). In the lowlands, paddy rice cultivation with irrigation may be possible, where two-wheel tractors have potential. In humid areas, animal traction faces clear disadvantages because of the high prevalence of diseases (i.e. trypanosomiasis) and lacking forage (Havard and Le Thiec, 1999; Mrema *et al.*, 2008). This undermines the use of bovines and equids, too, who 'seldom flourish in the humid and semi-humid tropics' (Sims and Kienzle, 2006). This changes at the edges of the humid zone, where forage opportunities are higher and health risks are lower (Havard and Le Thiec, 1999).

Soil texture

Soil texture also has a bearing on the three technological pathways because they affect soil workability and power requirements (Jones *et al.*, 2013). Broadly speaking, one can distinguish between light and heavy soils. Light soils contain more sandy particles, whereas heavy soils contain more clay or silt particles, which enhances moisture retention (Jones *et al.*, 2013). This makes light sandy soils easier to work with than heavy silt and clay soils (Jones *et al.*, 2013). Next to mineral contents, soil moisture can also matter as some soils are easy to work with regardless of soil moisture conditions, whereas others are only workable with adequate moisture, in particular when little farm power is available (Jones *et al.*, 2013).[6] Farmers can adapt to soil types to some degree by choosing different tillage methods, but soil types still have a bearing on the technological pathways (Stout and Cheze, 1999).

Light soils (i.e. sandy and loamy soils), which are common in arid areas, require limited farm power for tillage; hence, even manual hoeing is relatively easy (Ehui and Polson, 1993). Animal traction is an option for farmers aiming to replace human power since they generate sufficient farm power for such soils (Houssou *et al.*, 2013). On very light soils, equids (e.g. donkeys) and cows can be used as draught animals, whereas oxen can be used where power requirements are higher (Ellis-Jones *et al.*, 2005; Pearson and Vall, 1998). An alternative is the use of two-wheel tractors (Baudron *et al.*, 2019b; Kahan *et al.*, 2018; Kebede and Getnet, 2016). Kahan *et al.* (2018) have argued that 'land preparation and tillage are more effectively conducted by ploughing with

[6]Soil workability also depends on factors such as 'organic matter content, soil consistency/bulk density, the occurrence of gravel or stones in the profile or at the soil surface and the presence of rock outcrops or continuous hard rock at shallow depth' (Jones *et al.*, 2013).

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

2WTs on light and stone-free soils and within localities where the topography is suitable' (p. 10). Light sandy soils are, for example, arenosols, which are common in the Sahel region as well as parts of Eastern and Southern Africa (see Jones *et al.*, 2013, for an excellent overview of soil types in Africa). Importantly, while easier to work, such soils are also vulnerable to soil erosion; hence, soil-conserving farm practices are necessary (Jones *et al.*, 2013). In Ethiopia, soils that are considered too sandy are typically not mechanized (Berhane *et al.*, 2020). Pearson and Vall (1998) also have shown that some areas in Burkina Faso and Niger do not allow mechanization as soils are too sandy and rainfalls too low.

On heavy soils (e.g. silt and clay soils), which are common in more humid areas, more farm power is needed for land preparation (Binswanger and Donovan, 1987). On such soil, plowing with draught animals is very difficult under dry conditions (Stout and Cheze, 1999). Animal traction typically requires the use of two or three pairs of oxen – if feasible at all (Mrema *et al.*, 2020). Two-wheel tractors are often not suitable under such conditions, for example, in heavy and moist vertisols (Baudron *et al.*, 2015, 2019b; Kahan *et al.*, 2018). Hence, tractors are more likely to have a comparative advantage (Binswanger and Donovan, 1987). In Nigeria, Takeshima and Lawal (2020) find higher tractor use rates in areas with higher soil workability and lower clay content. In Tanzania, Mrema *et al.* (2020) find that 'lower-horsepower 4WTs were preferred in areas where the soils are light, whereas larger 4WTs were preferred where heavy clay soils are dominant' (p. 478). However, it is also possible to see mixed systems. In Senegal, farmers use machinery exclusively for power-intensive operations, and the use of animal draught power is mainly used for control-intensive operations (Tadesse *et al.*, 2019).

The comparative advantage of tractors on heavy soils is partly reduced when farmers practice when 'power-saving cropping systems' such as Conservation Agriculture (Baudron *et al.*, 2015). Using Conservation Agriculture tools that avoid soil inversion such as rippers or direct planters reduces the farm power needs by around half as compared to when using plows and allows farmers to work earlier (Baudron *et al.*, 2015, 2019b; Sims and Kienzle, 2006). Baudron *et al.* (2019b) argue that 'reduced or no-tillage could make the use of two-wheel tractors for crop establishment viable in most of Southern Africa' (p. 155). In many parts of Africa, including the humid and sub-humid zones, which are often characterized by infertile and weathered residual soils, continuous tillage would lead to a further decline in soil quality (e.g. soil erosion); hence, Conservation Agriculture appears to be the only appropriate practice (Ehui and Polson, 1993; Sims and Kienzle, 2006).

Conservation Agriculture also eases the workload for draught animals. Baudron *et al.* (2015) also see scope for animal-traction-based Conservation Agriculture such as the Zambia 'Magoye ripper', which 'allows for larger areas to be planted quickly while reducing power requirements' (p. 893). Awoke *et al.* (2015) also reported a reduced tillage time to improve the timeliness of tillage and planting operations with animal-drawn ripping tillage in central semi-arid Ethiopia. However, animal-traction-based Conservation Agriculture is also associated with some challenges. For example, Conservation Agriculture aims to keep crop residues to ensure better soil cover, but crop residues are a major source of forage for draught animals (Asamanew, 1991; Baudron *et al.*, 2015; Wilson, 2003).

Production type: Surface irrigation versus dryland

Surface irrigation versus dryland cultivation matters insofar as two-wheel tractors have a unique comparative advantage in surface irrigation rice production as they do not sink in and get easily stuck as compared to heavier four-wheel tractors (Adamu *et al.*, 2014). It is therefore not surprising that two-wheel tractors are most common in rice-based irrigated farming systems (Mrema *et al.*, 2018, 2020). In such systems, draught animals can also have a comparative advantage. For example, they are used in irrigated fields along the Nile (Starkey, 2000) and irrigated fields in Ethiopia (Tafera, 2011). Baudron *et al.* (2015) have argued that two-wheel

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

tractors 'produce enough traction to plough wet paddy fields, but not dry soils in rainfed conditions' (p. 984). In dryland systems, tractors may thus have a comparative advantage – unless 'power-saving cropping systems' such as Conservation Agriculture are practiced (see 'Soil Texture' section).

Topography

The topology of farm areas can shape the comparative advantage of the three technological pathways. In general, all technological solutions are more difficult to use in hilly and sloped lands. However, four-wheel tractors are particularly difficult and at times impossible to operate in hilly areas and steep valleys and there is a high risk of overturning (Pearson and Vall, 1998). In hilly areas, animal traction and two-wheel tractors have a comparative advantage over four-wheel tractors (Cerutti *et al.*, 2014; Pearson and Vall, 1998; Van Loon *et al.*, 2020). In Ethiopia, Berhane *et al.* (2020) have shown that tractors are typically not used on sloped and steep fields, and Tefera (2011) has argued that draught animals have an advantage on sloppy hills and rugged terrains. In Tanzania, two-wheel tractor ownership is concentrated in regions with 'relatively high latitudes' (Mrema *et al.*, 2020). However, in very hilly terrain, animal traction can be unfeasible (Havard and Le Thiec, 1999). Also, the performance of some two-wheel tractors may decrease at higher altitudes due to low oxygen for combustion, which is in contrast to 4WTs which are typically equipped with high-altitude compensator devices.

Tree cover, stumps, and stones

The prevalence of trees, stumps, and stones can also shape mechanization trajectories (Berhane *et al.*, 2020; Daum and Birner, 2017). In general, tree-based farming systems are more difficult to mechanize (Cramb and Thepent, 2020; Pingali *et al.*, 1987). This explains why tractor use in Ghana ranges from as few as 2% in parts of the forest zone to as many as 88% in the savannah zone (Diao *et al.*, 2020). In crop-based farming systems, trees affect the workability of animal traction as well as two-wheel tractors and four-wheel tractors. However, smaller and more versatile mechanization solutions such as animal traction and two-wheel tractor have a comparative advantage due to the higher maneuverability of machinery (Baudron *et al.* 2015, 2019b; Van Loon *et al.*, 2020). For example, two-wheel tractors have a more narrow track width than four-wheel tractors; hence, they can operate more easily in fields with trees (Baudron *et al.*, 2015). Where farmers want to use tractors, substantial investments in de-stumping are needed to avoid costly breakdowns (Diao *et al.*, 2018; Pingali *et al.*, 1987). Next to trees, tree stumps and stones are another challenges. Both two-wheel and four-wheel tractors can be damaged by stones and are best used on stone-free soils (Baudron *et al.*, 2015; Kahan *et al.*, 2018). In Ethiopia, stony fields are typically not mechanized by two-wheel or four -wheel tractors but are limited to animal traction as stones can damage the plows (Berhane *et al.*, 2020).

Mixed farming (crop-livestock-integration)

According to Ellis-Jones *et al.* (2005), animal traction is used 'most successfully where there is the integration of crop and livestock systems' (p. 279). In such farming systems, the main function of livestock is often the provision of farm power, but livestock provides additional 'economic functions including the provision of manure to maintain or improve soil fertility and the more traditional outputs such as milk, meat, hides, and skins for household use or sale' (p. 279). Pingali *et al.* (1987) have argued that the 'high-rainfall, semi-arid zone, and the sub-humid zone are ideal for such integration of crops and livestock' (p. 109) and 'for intensive farming and draught power' (p. 122).

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

Pasture, fodder, and water availability

The availability of pastures and water heavily influences the comparative advantages of animal traction vis-à-vis motorized mechanization. Animal traction requires farmers to have enough pastures (or land for forage production), as well as sufficient water at all times, or else animals suffer, become less productive, or even die. In areas where ample grazing land and water are available, the purchase and maintenance costs for animal traction are lower compared to purchasing and maintaining tractors (Binswanger, 1986; Diao *et al.*, 2020; Pearson and Vall, 1998). In contrast, two-wheel and four-wheel tractors appear to be the best option for farmers where animal traction is constrained by a lack of pastures and sufficient water.

In many parts of Africa where animal traction is used, the provision of animal feed has always been a challenge during the extended dry season, in particular in arid areas (Ellis-Jones *et al.*, 2005). As such, animals are often in poor condition at the end of the dry season, which is when they are expected to work hardest (Ellis-Jones *et al.*, 2005). In Ethiopia, animal performance is usually limited as draught oxen are in weak conditions during the main work season (Wilson, 2003).

Population growth and market demand put additional pressure on pastures and hence incentivize farmers to shift toward motorized mechanization (Baudron *et al.*, 2015; Binswanger-Mkhize and Savastano, 2017; Diao *et al.*, 2020; Ehui and Polson, 1993; Ruthenberg, 1980; Pingali and Binswanger, 1984; Pingali *et al.*, 1987). Across many parts of Africa, communal grazing areas are under pressure and feed shortages are becoming a serious challenge (Baudron *et al.*, 2015; Ellis-Jones *et al.*, 2005). In Ethiopia, which has a long culture of animal traction, the reduction of pastures is one of the reasons why the prices for animal traction services have doubled in the last two decades, making motorized mechanization more attractive (Berhane *et al.*, 2020; Takele and Selassie, 2018). Another reason is that the demand for meat is increasing, affecting the costs of oxen (Birhanu, 2019). Kahan *et al.* (2018) have argued that '2WTs may make inroads in areas where the costs of maintaining draught animals are high (for example, because of animal health concerns and feed shortages)' (p. 10).

The unfolding climate crisis is putting additional pressure on grazing land and water bodies in many areas in Africa (Ellis-Jones *et al.*, 2005). In Ghana, lacking access to feed during the dry season increasingly constrains animal traction (Houssou *et al.*, 2013). Mrema *et al.* (2008) attribute the decline of animal traction in parts of Eastern and Southern Africa to recurrent droughts. In Tanzania, a recurrent and prolonged drought killed 50% of the oxen that were used as draught animals and caused a rise in the use of two-wheel tractors (Mrema *et al.*, 2020). An alternative to using two-wheel or four-wheel tractors can be the use of more draught-resilient animals such as donkeys, which have lower feed and water requirements than cattle, however, are also less powerful and traditionally only used for lighter tasks (Ellis-Jones *et al.*, 2005; Panin, 1995; Pearson and Vall, 1998; Starkey, 2000).

Animal disease prevalence

As emphasized by Ellis-Jones *et al.* (2005), 'good animal health is a prerequisite for the success of animal traction' (p. 285). Hence, the prevalence of animal diseases is a major factor determining the comparative advantages of the three technological trajectories, in particular the use of animal traction (Starkey, 2000). In forested and humid parts of Africa, tsetse flies are common (see Schaub, 2017, for an excellent map of tsetse fly distribution in Sub-Saharan Africa), a vector of animal diseases such as trypanosomiasis (Sims and Kienzle, 2006). This undermines the use of animal traction in much of Central Africa (Alsan, 2015; Pingali *et al.*, 1987) and the coastal areas of West Africa (Ehui and Polson, 1993) but also parts of Eastern Africa, for example, in Tanzania (Mrema *et al.*, 2020). Moreover, in large parts of Eastern and Southern Africa, tick-borne diseases (e.g. East Coast fever) are highly prevalent (Baudron *et al.*, 2015; Sims and Kienzle, 2006). Mrema *et al.* (2008) attribute the decline of animal traction in parts of Eastern and Southern Africa to epidemics of livestock diseases. In Western Africa, trypanosomiasis-tolerant cattle breeds such as the West African shorthorn, Sanga, and N'dama are used as draught animals; however, they are less powerful compared to other cattle and, as noted by Houssou *et al.* (2013), while these breeds do not die from trypanosomiasis, their productivity can still be affected and they suffer from 'abortions, infertility, slow growth, and long calving intervals'. Pearson and Vall (1998) have argued that measures to reduce tsetse flies – which are the vectors for trypanosomiasis – have enabled the expansion of the use of working cattle into more sub-humid zones.

Heat and humidity stress

In hot climates, temperature and humidity stress are other aspects affecting the three technological pathways. Temperature and humidity stress can undermine animal health, animal welfare, and performance. Draught animals have to work in direct sunlight and without shade, limiting the number of hours draught animals can work, in particular in hot and humid climates (Pearson and Vall, 1998). As pointed out by Wilson (2003), draught animals in many parts of Africa have to work 'frenetically' during periods characterized by high temperatures. These difficulties are accelerated as animals are typically in poor conditions when they have to work at the end of the dry season due to lacking feed (Ellis-Jones *et al.*, 2005; Wilson, 2003). High workloads and heat stress make animal susceptible to animal disease (Wilson, 2003).

Temperature and humidity stress affects not only animal traction but also the manual workers and operators of two-wheel tractors, who equally have to conduct heavy physical work to control the walk-behind tractors in direct sunlight and without shade. Hence, where heat and humidity stress is large, four-wheel tractors appear to have a comparative advantage. Mrema *et al.* (2008) highlight the need for farm mechanization 'in tropical areas where high temperatures and humidity render fieldwork relying on human muscle power quite difficult' (p. xii).

Farm sizes and fragmentation

Farm sizes and fragmentation also affect the three technological pathways. All three mechanization technologies, including animal traction, two-wheel tractors, and four-wheel tractors, are associated with economics of scales, disadvantaging smallholder farmers who operate on small and fragmented plots. Hence, there is evidence from various African countries showing that large farms often mechanize earlier than small farms (e.g. Berhane *et al.*, 2020; Takeshima, 2017). While all three technological pathways are associated with such a mechanization divide, animal traction and two-wheel tractors are better adapted to smaller farm sizes and associated with lower economies of scale as compared to tractors. Sims and Kienzle (2006) have argued that it is 'generally not economically feasible for a smallholder farmer, with a typical landholding of up to 5 ha, to own a tractor' (p. xiv).

Baudron *et al.* (2015) and Kahan *et al.* (2018) have argued that two-wheel tractors have a comparative advantage (and are 'likely to outcompete') over four-wheel tractors where landholdings are small and fragmented. Under such conditions, four-wheel tractors are 'difficult to maneuver' (Kahan *et al.*, 2018). In Ethiopia, Berhane *et al.* (2020) have argued that 'land fragmentation and the small farm plots in many parts of Ethiopia further complicate the use of agricultural machines', in particular four-wheel tractors. According to Pingali *et al.* (1987), animal tractions are more effective than tractors where machinery service markets are difficult to establish as farm sizes are small. In contrast, four-wheel tractors have a comparative advantage where farms and plots are large. However, it is important to keep in mind that the sizes of four-wheel tractors vary significantly (see the 'How many wheels do tractors need?' section) and that there are also small horsepower tractors (category 1 tractors) that are similar in size compared to two-wheel tractors.

Samberg *et al.* (2016) offer a great map showing average farm size across Africa at the sub-national level, allowing some insights into where small farm mechanization options (i.e. animal traction and two-wheel tractors) have a comparative advantage and where large farm mechanization options (i.e. four-wheel tractors) have a comparative advantage. It is important to keep in mind that four-wheel tractors can also vary in power and size.

Institutional solutions such as asset-sharing arrangements can reduce the comparative disadvantage of four-wheel tractors where farms a small and fragmented to a certain degree. However, setting up such arrangements can be hampered by several challenges. For one, mechanization service markets are more difficult to set up where farmers have small and fragmented plots as this raises transaction costs (Daum and Birner, 2017; Daum *et al.*, 2021; Sims and Kienzle, 2006). Moreover, in many rain-fed farming systems, in particular in arid and semi-arid areas, farmers demand mechanization services during a short period and usually all at once due to shared rainfall and temperature patterns, which makes it difficult to reach economics of scale for service providers (Daum, 2023; Diao *et al.*, 2020; Mrema *et al.*, 2008).

Labor availability

Labor availability can also shape the comparative advantage of the three technological pathways as the three technologies replace manual labor to different degrees. While animal traction can help to reduce the labor burden associated with farming, it does so to a lower degree as compared to tractors. Sims and Kienzle (2016) show animal traction can reduce the workload associated from around 500 labor hours per hectare to 60 hours – however, tractors need only 1–2 hours. In a review of labor effects of farm mechanization, Pingali *et al.* (1987) found that 22 of 24 studies found a reduction in labor when tractors replaced draught animals – with 12 studies documenting labor reductions of more than 50%. As highlighted by Wilson (2003), whereas four-wheel and two-wheel tractors are typically operated only by one person, operating and controlling draught animals often involve several people (up to 3–4 depending on the number of animals), even though in some areas such as parts of Ethiopia only one person operates and controls draught animals.

Importantly, animal traction is associated with labor use not only in the farm season when animals are used but also in the off-farm season for producing fodder, fetching water, and herding and tending animals (Ehui and Polson, 1993; Wilson, 2003). Moreover, unlike tractors, draught animals have to be trained (Wilson, 2003). The higher labor use for using draught animals comes with large opportunity costs, undermining the pursuit of other productive or reproductive activities such as farm work, off-farm work, care, and leisure (Delgado, 1989; Ehui and Polson, 1993; Wilson, 2003). In Ghana, Houssou *et al.* (2013) observed a decline in animal traction because of the 'increasing school enrolment of the youth who serve as plowboys'. This concern has also been noted by Ellis-Jones *et al.* (2005).

Hence, with lower labor availability, farmers are more likely to use two-wheel and four-wheel tractors rather than using animal traction. Four-wheel tractors have an increasing comparative advantage over two-wheel tractors with declining labor availability and rising rural wages as they are more productive than two-wheel tractors. In Africa, labor availability is on the decline, and rural wages are on the rise in some countries (Daum, 2023; Diao *et al.*, 2020; Sims and Kienzle, 2006). In Ethiopia, structural transformation caused the real wages of unskilled laborers in rural areas to rise by more than 50% in the last two decades (Berhane *et al.*, 2020). In Ghana, a rise in the non-agricultural economy has led to rising rural wages, making labor costs account for 45% of the overall input costs of farms (Diao *et al.*, 2014).

Energy availability and costs

Energy availability and costs also influence the comparative advantages and disadvantages of the three technological pathways. The availability and costs of energy are for tractors and the availability and costs of pasture and water are for animal traction. Sims and Kienzle (2006) show that fuel costs constitute up to 70% of the operating cost of tractors. In areas, with high fuel costs, tractors have a comparative disadvantage. Baudron *et al.* (2015) have argued that (two-wheel) tractors only have an advantage over animal traction where 'fuel is available and affordable'. Mrema *et al.* (2008) also highlighted that high energy costs can be 'a drawback' to motorized mechanization as the 'price of fuel and availability of regular supplies bears directly on the profitability of using mechanical power sources in agriculture' (p. 39).

Discussion and policy implications

Farm mechanization is essential to ensure that African farmers have sufficient farm power (Baudron *et al.*, 2015; Baudron *et al.*, 2019; Diao *et al.*, 2014; Silva *et al.*, 2019). There are big debates on which of the three major technological pathways toward farm mechanization (animal traction, two-wheel tractors, four-wheel tractors) should be supported by African governments and development partners. Based on the premise that there are no blueprint answers on which technological pathway is 'best' but only answers on which one 'best fits' the respective conditions, this paper has introduced a novel 'best-fit' framework to analyze the comparative advantages and disadvantages of the three technological pathways vis-à-vis the large agroecological and socioeconomic heterogeneity of African farming systems. The results suggest that all three forms of mechanization are associated with areas where they 'best fit'. This confirms Mrema *et al.* (2008) who argue that no mechanization pathway is 'exclusively suitable for all regions and districts' and Baudron *et al.* (2015) and Kahan *et al.* (2018) who see a 'niche' for all mechanization types in Africa.

Animal traction continues to have a place in areas with small and fragmented farm holdings in semi-arid and semi-humid agroecological zones with light soils as long as pasture and water are available. Two-wheel tractors also have a comparative advantage where farms are small and fragmented and soils are light and where animal diseases undermine the use of draught animals. Two-wheel tractors also 'make inroads' (Kahan *et al.*, 2018) where population growth, farming system evolution, and climate change put pressure on pastures and land for fodder production (Baudron *et al.*, 2015; Kahan *et al.*, 2018; Mrema *et al.*, 2020). This has been observed, for example, in Ethiopia and Tanzania (Berhane *et al.*, 2020; Mrema *et al.*, 2020). Four-wheel tractors have a comparative advantage where farms are large and where two-wheel tractors lack the power to plough under rainfed conditions on more heavy soils and in areas where there is high climate variability and unpredictable rainfall patterns. The scope for two-wheel tractors widens significantly where power-saving farming practices such as Conservation Agriculture are used (Awoke *et al.*, 2020; Baudron *et al.*, 2015, 2019b) and the scope for four-wheel tractors widens where affordable and reliable asset-sharing arrangements can be set up. Mechanization service markets are on the rise across various African countries (Adu-Baffour *et al.*, 2019; Berhane *et al.*, 2020; Cabral and Anamor, 2022; Daum and Birner, 2017; Takeshima and Lawal, 2020), and digital technologies such as Uber-type solutions may facilitate them (Daum *et al.*, 2021).

The 'best-fit' framework can help governments and development partners to better understand which technological pathways should be promoted with accompanying institutions and investments given the existing agroecological and socioeconomic conditions of their country's farming systems. Governments and policymakers who push farm mechanization solutions (animal traction, two-wheel tractors, four-wheel tractors) against fundamental agroecological and socioeconomic factors are likely to fail in their efforts, as the history of farm mechanization in Africa has shown (Pingali *et al.*, 1987; Sims and Kienzle, 2006). Hence, policies and investments toward farm mechanization should be guided by agroecological and socioeconomic frame conditions (see also Mrema *et al.*, 2008) and not political considerations such as an appeal for large 'modern' tractors (Cabral, 2022; Cabral and Amanor, 2022). This applies in particular to the role

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

of animal traction, which continues to have a comparative advantage in parts of Africa but tends to be neglected by policymakers (Daum and Birner, 2017; Daum *et al.*, 2022; Starkey, 2000) due to its image as being 'archaic and antiquated' (Wilson, 2003, p. 21). Starkey (2000) has long argued that the spread of animal traction is undermined by competing subsidies and legislation.

The 'best-fit' framework highlights which agroecological and socioeconomic factors are of relevance when assessing the comparative advantages and disadvantages of the three farm mechanization pathways. The application of the framework also gives a first approximation of which farm mechanization pathway 'best fits' in different parts of Africa, hence allowing some coarse geolocation. However, while this provides governments and development partners with some guidance, the decision on which mechanization solutions to prioritize and support in different countries should be informed by a more in-depth analysis of the field situation at the country level (Mrema *et al.*, 2008). Such an in-depth analysis could be part of the formulation of national agricultural mechanization strategies, which have long been advocated by the Food and Agriculture Organization (FAO) of the United Nations. These strategies aim to guide farm mechanization based on a careful analysis of the present situation and the development of future scenarios (FAO & AUC, 2018; Sims and Kienzle, 2006). Assessing both the present and likely future situation is important due to technological advancements, as some agroecological and socioeconomic factors can change quickly, and setting up sound enabling environments takes time.

The presented 'best-fit' framework can help stakeholders to ensure an objective approach when assessing the comparative advantages and disadvantages of the three technological pathways when formulating such agricultural mechanization strategies. Importantly, such an analysis partly hinges on better data. For example, investments in soil mapping are needed to better understand farm power requirements and optimal tractor sizes (Diao *et al.*, 2020). As part of the more in-depth analysis at the country level, farmers should play a central role, as they 'have detailed and practical knowledge of their own production systems' (Sims and Kienzle, 2006, p. xvii). However, it is important to keep in mind that farmers' decision-making is not always 'rational', for example, they may find large tractors more attractive than small ones due to status considerations. Also, aspects such as autonomy may affect farmers' preferences for the three mechanization solutions, for example, if they think it is better to *own* smaller equipment (e.g. animal traction sets or two-wheel tractors) or *hire* larger equipment (e.g. four-wheel tractors). Farmers' mechanization needs and preferences may also differ by culture and gender, among others.

The 'best-fit' framework explicitly excludes exogenous factors which can be shaped by government and development partners. However, a more in-depth analysis at the country level should also pay attention to how easy it is to set up the appropriate enabling environment for the prioritized technological pathways, which requires an analysis of culture and tradition, existing infrastructure, and knowledge and skills levels. For example, introducing animal traction where there is no tradition of animal husbandry is a major undertaking (Mrema *et al.*, 2008). The best-fit framework focuses on the comparative advantages and disadvantages of the three mechanization solutions mainly regarding on-farm activities (i.e. land preparation) and pays more limited attention to other aspects such as the multiple side benefits (e.g. meat, milk, hide, manure, and biogas) from the use of animal traction (see the 'The future of animal traction' section) and the multifunctionality of two-wheel tractors (see the 'How many wheels do tractors need?' section), which are important to consider, however. When applying the "best-fit" framework at the county level, it is also important to keep in mind that the sizes of four-wheel tractors vary significantly (see the 'How many wheels do tractors need?' section.). It is also important to keep in mind that there are constant technological advancements such as concerning robots and drones, which become more relevant in the future (Daum, 2021; FAO, 2022).

All three pathways hinge on public support (Daum and Birner, 2020, Diao *et al.*, 2020; FAO & AUC, 2018; Kahan *et al.*, 2018; Mrema *et al.*, 2008). The extent to which public support is guided toward the three technological options shapes – to some degree – their comparative advantage.

For example, the comparative advantage of animal traction changes with the public breeding efforts toward obtaining more powerful and more disease-tolerant and drought-resistant draught animals and with the public, applied investments in better feeding strategies. Similarly, the comparative advantage of tractors changes with increased efforts on knowledge and skills development or road infrastructure development, which facilitates the setup of tractor service markets. While, in some countries, one mechanization solution may have a future, in countries with diverse conditions, all mechanization pathways may be of relevance and warrant support. The advantage of smaller versus larger mechanization solutions can also depend on environmental policies and investments (Daum *et al*., 2023).

The 'best-fit' framework is based on the premise that innovation processes do not take place in an institutional vacuum but are shaped significantly by the agricultural innovation system, which in turn is largely determined by governments and development partners. For this, governments and development partners should know what mechanization solutions 'best-fit' their country's farming system to optimize priority setting. However, ultimately, innovation processes related to farm mechanization should be driven by market actors, that is, farmers and private companies, who are best able to find 'best-fit' solutions and respond to changing agroecological and socioeconomic conditions.

Acknowledgements. We would like to thank the editor and the two reviewers for their time and valuable comments. We would also like to thank the "Program of Accompanying Research for Agricultural Innovation" (PARI), which is funded by the German Federal Ministry of Economic Cooperation and Development (BMZ), for its financial support.

Competing interests. None.

References

Adamu F. A., Jahun B. G. and Babangida B. (2014). Performance Evaluation of power tiller in Bauchi state Nigeria. *Performance Evaluation* **4**, 10–14.

Adu-Baffour F., Daum T. and Birner R. (2019). Can small farms benefit from big companies' initiatives to promote mechanization in Africa? A case study from Zambia. *Food Policy* **84**, 133–145.

Alsan M. (2015). The effect of the tsetse fly on African development. *American Economic Review* **105**, 382–410.

André P., Delesalle E. and Dumas C. (2021). Returns to farm child labor in Tanzania. *World Development* **138**, 105181.

Asamanew G. (1991). *A study of the Farming Systems of Some Ethiopian Highland Vertisol Locations. Working Document.* Addis Ababa, Ethiopia: International Livestock Centre for Africa.

Awoke B.G., Baudron F., Antille D.L., Kebede L., Anawte D.A., Tikuneh D.B. and Aikins K.A. (2020). Evaluation of two-wheel tractor attached seeders used in conservation agriculture systems of Ethiopia. *ASABE 2020 Annual International Meeting*, 2000334, 1–9

Awoke B.G., Kebede L. and Hae K.K. (2015). Evaluation of conservation tillage techniques for maize production in the Central Rift Valley of Ethiopia. *Ethiopian Journal of Agricultural Sciences* **25**, 47–58.

Baudron F., Misiko M., Getnet B., Nazare R., Sariah J. and Kaumbutho P. (2019). A farm-level assessment of labor and mechanization in Eastern and Southern Africa. *Agronomy for Sustainable Development* **39**, 17.

Baudron F., Nazare R. and Matangi D. (2019b). The role of mechanization in transformation of smallholder agriculture in Southern Africa: experience from Zimbabwe. In Sikora R., Terry E.R., Vlek P. and Chitja, J. (eds), *Transforming Agriculture in Southern Africa. Constraints, Technologies, Policies and Processes.* London: Routledge.

Baudron F., Sims B., Justice S., Kahan D.G., Rose R., Mkomwa S., Kaumbutho P., Sariah J., Nazare R., Moges G. and Gérard B. (2015). Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheel tractors, conservation agriculture, and private sector involvement. *Food Security* **7**, 889–904.

Berhane G., Dereje M., Minten B. and Tamru S. (2020). The rapid–but from a low base–uptake of agricultural mechanization in Ethiopia: patterns, implications and challenges. In Diao X., Takeshima H. and Zhang X. (eds), *An Evolving Paradigm of Agricultural Mechanization Development: How Much Can Africa Learn from Asia?* Washington DC: International Food Policy Research Institute (IFPRI), pp. 329–375.

Bhattarai M, Singh G, Takeshima H. and Shekhawat R.S. (2020) Farm machinery use and the agricultural machinery industries in India. In Diao X., Takeshima H. and Zhang X. (eds), *An evolving paradigm of agricultural mechanization development: How much can Africa learn from Asia?* Washington DC: International Food Policy Research Institute, pp. 97–137.

Binswanger H. (1986). Agricultural mechanization: a comparative historical perspective. *The World Bank Research Observer* **1**, 27–56.

Binswanger H.P. and Donovan G. (1987). *Agricultural mechanization: issues and options*. Washington, DC:World Bank.

Binswanger-Mkhize H.P. and Savastano S. (2017). Agricultural intensification: the status in six African countries. *Food Policy*, **67**, 26-40.

Birhanu A.F. (2019). A review on Ethiopian meat production trends, consumption and meat quality parameters. *International Journal of Food Science and Agriculture* **3**, 267–274.

Boserup E. (1965). *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure*. London: Allen & Unwin.

Cabral L. (2022). Of zinc roofs and mango trees: tractors, the state and agrarian dualism in Mozambique. *The Journal of Peasant Studies* **49**, 200–224.

Cabral L. and Amanor K.S. (2022). Tractors, states, markets and agrarian change in Africa. *The Journal of Peasant Studies* **49**, 129–136.

Cerutti A.K., Calvo, A. and Bruun S. (2014). Comparison of the environmental performance of light mechanization and animal traction using a modular LCA approach. *Journal of Cleaner Production* **64**, 396–403.

Cramb R. and Thepent C. (2020). Evolution of agricultural mechanization in Thailand. In Diao X., Takeshima H. and Zhang X. (eds), *An evolving paradigm of agricultural mechanization development: how much can Africa learn from Asia?* Washington DC: International Food Policy Research Institute, pp. 165–201.

Dasgupta S., van Maanen N., Gosling S.N., Piontek F., Otto C. and Schleussner C.-F. (2021). Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. *The Lancet Planetary Health* **5**, e455–e465.

Daum T. (2021). Farm robots: ecological utopia or dystopia? *Trends in Ecology & Evolution* **36**, 774–777.

Daum T. (2023). Mechanization and sustainable agri-food system transformation in the global South. A review. *Agronomy for Sustainable Development* **43**, 1–26.

Daum T., Adegbola P.Y., Adegbola C., Daudu C., Issa F., Kamau G., Kergna A., Mose L., Ndirpaya Y., Oluwole F., Zossou R., Kirui O. and Birner R. (2022). Mechanization, digitalization, and rural youth-Stakeholder perceptions on three mega-topics for agricultural transformation in four African countries. *Global Food Security* **32**, 100616.

Daum T., Adegbola Y.P., Kamau G., Daudu C., Zossou R.C., Crinot G.F., Houssou P., Mose L., Ndirpaya Y., Wahab A. A., Kirui O. and Oluwole F.A. (2020). Perceived effects of farm tractors in four African countries, highlighted by participatory impact diagrams. *Agronomy for Sustainable Development* **40**, 1–19.

Daum T., Baudron F., Birner R., Qaim M. and Grass I. (2023). Addressing agricultural labour issues is key to biodiversity-smart farming. *Biological Conservation*, **284**, 110165.

Daum T. and Birner R. (2017). The neglected governance challenges of agricultural mechanisation in Africa insights from Ghana. *Food Security* **9**, 959–979.

Daum T. and Birner R. (2020). Agricultural mechanization in Africa: myths, realities and an emerging research agenda. *Global Food Security* **26**, 100393.

Daum T. and Birner R. (2021). The forgotten agriculture-nutrition link: farm technologies and human energy requirements. *Food Security* **14**, 395–409.

Daum T., Huffman W.E. and Birner R. (2018). How to create conducive institutions to enable agricultural mechanization: a comparative historical study from the United States and Germany. *Economics Working Papers 18009*. Iowa State University.

Daum T. and Kirui O. (2021). Mechanization along the value chain. In Baumüller H., Admassie A., Hendriks S., Tadesse G. and von Braun J. (eds.), *From Potentials to Reality: Transforming Africa's Food Production*. Bern: Peter Lang, pp. 67–73.

Daum T., Villalba R., Anidi O., Mayienga S.M., Gupta S. and Birner R. (2021). Uber for tractors? Opportunities and challenges of digital tools for tractor hire in India and Nigeria. *World Development* **144**, 105480.

Delgado C.L. (1989). *The changing economic context of mixed farming in savanna West Africa: a conceptual framework applied to Burkina Faso*. Washington, DC: International Food Policy Research Institute.

Diao X., Agandin J., Fang P., Justice S.E., Kufoalor D.S. and Takeshima, H. (2018). Agricultural mechanization in Ghana: Insights from a recent field study. IFPRI Discussion Paper 1729. Washington, DC: International Food Policy Research Institute.

Diao X., Cossar F., Houssou N. and Kolavalli S. (2014). Mechanization in Ghana: emerging demand, and the search for alternative supply models. *Food Policy* **48**, 168–181.

Diao X., Takeshima H. and Zhang X. (2020). *An Evolving Paradigm of Agricultural Mechanization Development: How Much can Africa Learn from Asia?*: Washington, DC: International Food Policy Research Institute.

Ehui S. and Polson R. (1993). A review of the economic and ecological constraints on animal draught cultivation in Sub-Saharan Africa. *Soil and Tillage Research* **27**, 195–210.

Ellis-Jones J., O'Neill D., Riches C. and Sims B. (2005). Farming systems: Future challenges for the use of draught animals in agricultural development with emphasis on Sub-Saharan Africa. *Annals of Arid Zone* **44**, 277–296.

FACASI (2019). *Farm Mechanization and Conservation Agriculture for Sustainable Intensification Final Review and Closing Meeting*. Available at http://facasi.act-africa.org/file/20170626_agricultural_mechanization_and_small_scale_agriculture_case_study_evidence_from_eastern_and_southern_africa.pdf

https://doi.org/10.1017/S0014479723000091 Published online by Cambridge University Press

FAO (2022). *The State of Food and Agriculture 2022. Leveraging Automation in Agriculture for Transforming Agrifood Systems.* Rome: Food and Agriculture Organisation.

FAO & AUC (2018). *Sustainable Agricultural Mechanization: A Framework for Africa.* Food and Agriculture Organisation, Rome and African Union Commission, Addis Ababa.

Fuglie K., Gautam M., Goyal A. and Maloney W.F. (2019). *Harvesting Prosperity: Technology and Productivity Growth in Agriculture.* Washington, DC: World Bank.

Gebregziabher S., Mouazen A.M., Van Brussel H., Ramon H., Nyssen J., Verplancke H., Behailu M., Deckers J. and De Baerdemaeker J. (2006). Animal drawn tillage, the Ethiopian ard plough, maresha: a review. *Soil and Tillage Research* **89**, 129–143.

Havard M. and Le Thiec G. (1999). Environmental influences on the adoption of animal traction. In Starkey P. and Kaumbutho P. (eds), *Meeting the Challenges of Animal Traction. A Resource Book of the Animal Traction Network for Eastern and Southern Africa (ATNESA).* London: Intermediate Technology Publications, pp. 60–67.

Havard M., Njoya A., Pirot R., Vall E. and Wampfler B. (2000). Challenges of Animal Traction Research and Development in West and Central Africa at the eve of the 21st Century. In Kaumbutho P., Pearson A., Simalenga T. (eds), *Empowering farmers with animal traction : Proceedings of the workshop of the Animal Traction Network for Eastern and Southern Africa (ATNESA)*, 20-24 September 1999, Mpumalanga, South Africa. ATNESA, Nairobi.

Hegazy R., Schmidley A., Bautista E., Sumunistrado D., Gummert M. and Elepaño A. (2013). *Mechanization in Rice Farming—Lessons Learned from Other Countries.* Laguna: Asia Rice Foundation (ARF) Publication.

Heinimann A., Mertz O., Frolking S., Egelund Christensen A., Hurni K., Sedano F., Parsons Chini L., Sahajpal R., Hansen M. and Hurtt G. (2017). A global view of shifting cultivation: Recent, current, and future extent. *PloS one*, **12**(9), e0184479.

Herrmann K. (1994). Die Geschichte der Einachsschlepper. In Fok O., Wendler U. and Wiese R. (eds), *Vom Klepper zum Schlepper. Zur Entwicklung der Antriebskräfte in der Landwirtschaft.* Ehestorf: Freilichtmuseum am Kiekeberg, pp. 287–302.

Houssou N., Kolavalli S., Bobobee E. and Owusu V. (2013). *Animal Traction in Ghana. Ghana Strategy Support Program Working Paper No. 34.* International Food Policy Research Institute, Accra.

ILO (2021) *Child Labor: Global estimates 2020, trends and the road forward.* New York: International Labor Office and UNICEF. https://www.ilo.org/ipec/Informationresources/WCMS_797515/lang–en/index.htm

Jahnke H.E. (1982). *Livestock Production Systems and Livestock Development in Tropical Africa.* Kiel: Kieler Wissenschaftsverlag Vauk.

Johnston D., Stevano S., Malapit H.J., Hull E. and Kadiyala S. (2018). Time use as an explanation for the agri-nutrition disconnect: evidence from rural areas in low and middle-income countries. *Food Policy* **76**, 8–18.

Jones A., Breuning-Madsen H., Brossard M., Dampha A., Deckers J., Dewitte O., Gallali T., Hallett S., Jones R., Kilasara M., Le Roux P., Micheli E., Montanarella L., Spaargaren O., Thombiano L., Van Ranst E., Yemefack M. and Zougmoré R. (2013). Soil atlas of Africa. European Commission, Publications Office of the European Union, Luxembourg.

Justice S. and Biggs S. (2020). The spread of smaller engines and markets in machinery services in rural areas of South Asia. *Journal of Rural Studies* **73**, 10–20.

Kahan D., Bymolt R. and Zaal F. (2018). Thinking outside the plot: insights on small-scale mechanisation from case studies in East Africa. *The Journal of Development Studies* **54**, 1939–1954.

Kebede L. and Getnet B. (2016). Performance of single axle tractors in the semi-arid central part of Ethiopia. *Ethiopian Journal of Agricultural Sciences* **27**, 37–53.

Kirui O. (2019). The agricultural mechanization in Africa: micro-level analysis of state drivers and effects. ZEF-Discussion Papers on Development Policy No. University of Bonn.

Lawrence, P.R. and Pearson, R.A. (2002). Use of draught animal power on small mixed farms in Asia. *Agricultural Systems* **71**, 99–110.

Lowder S.K., Sánchez M.V. and Bertini R. (2021). Which farms feed the world and has farmland become more concentrated? *World Development* **142**, 105455.

Mano Y., Takahashi K. and Otsuka K. (2020). Mechanization in land preparation and agricultural intensification: the case of rice farming in the Cote d'Ivoire. *Agricultural Economics* **51**, 899–908.

Melaku T. (2011). Oxenization versus tractorization: options and constraints for Ethiopian farming system. *International Journal of Sustainable Agriculture* **3**, 11–20.

Mrema G.C., Baker D. and Kahan D. (2008). *Agricultural Mechanization in Sub-Saharan Africa: Time for a New Look.* Rome: Food and Agriculture Organisation.

Mrema G.C., Kahan D.G. and Agyei-Holmes A. (2020). Agricultural mechanization in Tanzania. In Diao X., Takeshima H. and Zhang X. (eds),*An Evolving Paradigm of Agricultural Mechanization Development: How Much Can Africa Learn from Asia?* Washington DC: International Food Policy Research Institute, pp. 457–496.

Mrema G.C., Kienzle J. and Mpagalile J. (2018). Current status and future prospects of agricultural mechanization in sub-saharan Africa (SSA). *Agricultural Mechanization in Asia, Africa and Latin America* **49**, 13–30.

O'Mara F.P. (2011). The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. *Animal Feed Science and Technology* **166–167**, 7–15.

Ogwuike P., Rodenburg J., Diagne A., Agboh-Noameshie A.R. and Amovin-Assagba E. (2014). Weed management in upland rice in sub-Saharan Africa: impact on labor and crop productivity. *Food Security* **6**, 327–337.

Panin A. (1995). Empirical evidence of mechanization effects on smallholder crop production systems in Botswana. *Agricultural Systems*, **47**(2), 199–210.

Pearson R.A. and Vall E. (1998). Performance and management of draught animals in agriculture in sub-Saharan Africa: a review. *Tropical Animal Health and Production* **30**, 309–324.

Pingali P. (2007). Agricultural mechanization: adoption patterns and economic impact. *Handbook of Agricultural Economics* **3**, 2779–2805.

Pingali P., Bigot Y. and Binswanger H.P. (1987). *Agricultural Mechanization and the Evolution of Farming Systems in Sub-Saharan Africa.* Washington, DC: World Bank.

Pingali P.L. and Binswanger H.P. (1984). *Population density and agricultural intensification: a study of the evolution of technologies in tropical agriculture*. Washington, DC: World Bank.

Ramaswamy N.S. (1998). Draught animal welfare. *Applied Animal Behaviour Science* **59**, 73–84.

Ruthenberg H. (1980). *Farming Systems in the Tropics.* Oxford: Oxford University Press.

Samberg L.H., Gerber J.S., Ramankutty N., Herrero M. and West P.C. (2016). Subnational distribution of average farm size and smallholder contributions to global food production. *Environmental Research Letters* **11**, 124010.

Schaub M. (2017). Second-order ethnic diversity: the spatial pattern of diversity, competition and cooperation in Africa. *Political Geography* **59**, 103–116.

Sebastian K. (2009). *Agro-Ecological Zones of Africa*. Washington, DC: International Food Policy Research Institute (datasets). Available at http://hdl.handle.net/1902.1/22616

Sebastian K. (2014). *Atlas of African Agriculture Research and Development – Revealing Agriculture's Place in Africa.* Washington, DC: International Food Policy Research Institute (IFPRI).

Sheahan, M., & Barrett, C. B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy*, **67**, 12–25.

Silva J.V., Baudron F., Reidsma P. and Giller K.E. (2019). Is labor a major determinant of yield gaps in sub-Saharan Africa? A study of cereal-based production systems in Southern Ethiopia. *Agricultural Systems* **174**, 39–51.

Sims B.G. and Kienzle J. (2006). *Farm Power and Mechanization for Small Farms in Sub-Saharan Africa.* Agricultural and Food Engineering Technical Report, Food and Agriculture Organisation (FAO), Rome.

Spielman D. and Birner R. (2008). *How innovative is your agriculture? Using innovation indicators and benchmarks to strengthen national agricultural innovation systems.* Washington, DC: World Bank.

Starkey P. (2000). The history of working animals in Africa. In Blench R. and MacDonald C. (eds), *The Origins and Development of African livestock: Archaeology, Genetics, Linguistics and Ethnography*, London: Routledge, pp. 478–502.

Stout B. and Cheze B. (1999). *CIGR Handbook of Agricultural Engineering Volume 3 Plant Production Engineering*. St. Joseph: American Society of Agricultural Engineers.

Tadesse G., Goundan A. and Sarr, S. (2019). Farm power transition and access in Senegal: Patterns and constraints. Invited paper presented at the 6th African Conference of Agricultural Economists, September 23-26, 2019, Abuja, Nigeria.

Takele A. and Selassie Y.G. (2018). Socio-economic analysis of conditions for adoption of tractor hiring services among smallholder farmers, Northwestern Ethiopia. *Cogent Food & Agriculture* **4**, 1453978.

Takeshima H. (2017). *Overview of the Evolution of Agricultural Mechanization in Nepal: A Focus on Tractors and Combine Harvesters. IFPRI Discussion Paper* **1662.** Washington DC: International Food Policy Research Institute, .

Takeshima H. and Lawal A. (2020). Evolution of agricultural mechanization in Nigeria. In Diao X., Takeshima H. and Zhang X. (eds), *An Evolving Paradigm of Agricultural Mechanization Development: How Much Can Africa Learn from Asia?*: Washington DC: International Food Policy Research Institute, pp. 423–456.

Tefera M. (2011). Oxenization versus tractorization: options and constraints for Ethiopian framing system. *International Journal of Sustainable Agriculture* **3**, 11–20.

Thierfelder C. (2021). *Animal Traction-Based Maize–Legume Conservation Agriculture*. Africa RISING Technology Brief. Ibadan, Nigeria: IITA.

Upton M. (2004). *The Role of Livestock in Economic Development and Poverty Reduction*. Pro Poor Livestock Policy Initiative Working Papers 12. Rome: Food and Agriculture Organisation.

Van Loon J., Woltering L., Krupnik T.J., Baudron F., Boa M. and Govaerts B. (2020). Scaling agricultural mechanization services in smallholder farming systems: case studies from sub-Saharan Africa, South Asia, and Latin America. *Agricultural Systems* **180**, 102792.

Van Vliet J.A., Schut A.G., Reidsma P., Descheemaeker K., Slingerland M., van de Ven G.W. and Giller K.E. (2015). De-mystifying family farming: features, diversity and trends across the globe. *Global Food Security* **5**, 11–18.

Williams T.O. (1997). Problems and prospects in the utilization of animal traction in semi-arid West Africa: evidence from Niger. *Soil and Tillage Research* **42**, 295–311.

Wilson R.T. (2003). The environmental ecology of oxen used for draught power. *Agriculture, Ecosystems & Environment* **97**, 21–37.

Win M.T., Belton B. and Zhang X. (2020). Myanmar's rapid agricultural mechanization: Demand and supply evidence. In Diao X., Takeshima H. and Zhang X. (eds), *An evolving paradigm of agricultural mechanization development: How much can Africa learn from Asia?*: Washington DC: International Food Policy Research Institute, pp. 263–284.

World Bank (2012). *Agricultural Innovation Systems – An Investment Sourcebook*. Washington, DC: World Bank.

Yun J.H. and Kim K.U. (2013). *Policy for Promotion of Agricultural Mechanization and Technology Development. Knowledge Sharing Program: KSP Modularization*. Rural Development Administration, Republic of Korea and Northern Agriculture Research Institute. Knowledge Sharing Program Development Research and Learning Network, Seoul.

Cite this article: Daum T, Seidel A, Awoke BG, and Birner R. Animal traction, two-wheel tractors, or four-wheel tractors? A best-fit approach to guide farm mechanization in Africa. *Experimental Agriculture*. https://doi.org/10.1017/S0014479723000091