Hohenheim Working Papers on Social and Institutional Change in Agricultural Development

Working Paper 012-2022

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

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Universität Hohenheim

April 2022

Hohenheim Working Papers on Social and Institutional Change in Agricultural Development (012-2022)

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Suggested citation: Daum, T., Seidel, A., Awoke, B., Birner, R. Animal traction, two-wheel tractors, or four-wheel tractors? A best-fit approach to guide farm mechanization in Africa. Hohenheim Working Papers on Social and Institutional Change in Agricultural Development. 012-2022. University of Hohenheim.

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Abstract

There are heavy - at times dogmatic - debates on which technological pathway toward farm mechanization - animal traction, two-wheel tractors, 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, the paper introduces a "best fit" framework that allows for assessing the comparative advantages and disadvantages of the three technological pathways in different agro-ecological and socio-economic 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.

Key Words

Agricultural mechanization, farm mechanization, draught animals, animal traction, four-wheel tractors, two-wheel tractors

Acknowledgments

We are equally grateful for the financial support from the "Program of Accompanying Research for Agricultural Innovation" (PARI), which is funded by the German Federal Ministry of Economic Cooperation and Development (BMZ).

1. Introduction

Governments and development partners across Africa promote farm mechanization to replace *hoe and cutlass* types of farming (Daum & Birner, 2020; FAO & AUC, 2018), which is the common mode of farming on 80% of African 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 & Kirui, 2021; FAO & AUC, 2018). The mechanization of land preparation is typically the first step of farm mechanization, making necessary the use of solutions pulling equipment such as plows, harrows, and rippers (Binswanger, 1986). The efforts of governments and development partners to promote farm mechanization are backed up by evidence from several African countries highlighting how labor constraints increasingly undermine agricultural land and labor productivity (Baudron et al., 2015; Baudron et al., 2019; Diao et al., 2014; Silva et al., 2019; Sims & Kienzle, 2006) and how mechanized farmers can raise land and labor productivity (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 has 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 & Pearson, 2002), including two-wheel tractors in wetland rice production, and small horspower four-wheel tractors in other farming systems (Diao et al, 2020; Pingali, 2007).

With Africa being at a mechanization crossroads, there are heavy – at times dogmatic - debates about which of these technological pathways should be pursued (Daum & 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 towards motorized mechanization (Pingali et al., 1987; Sims & 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 & Amanor, 2021; Mrema et al., 2008). In contrast, animal traction is often 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 (Pingali et al., 1987; Daum & Birner, 2020; Daum et al., 2022; Mrema et al., 2008). 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 are not efficient and have a limited potential to reduce the drudgery of farming (as discussed in Daum & 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 the respective agro-ecological and socio-economic contexts (see also Kahan et al., 2018; Mrema et al., 2008; Sims & 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 & 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 & 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 & 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, e.g., related to knowledge and skills development for tractor owners, operators, and technicians (Daum et al., 2018; Daum & Birner, 2017; Diao et al., 2020; FAO & AUC, 2018; Mrema et al., 2008).

While governments and development partners can in principle support all three technological pathways this can translate to expensive parallel structures, in particular when promoting both animal traction and motorized farm mechanization. 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 & Kienzle. 2006, p. 58) – an error that could be avoided with a better alignment of farm mechanization efforts with agro-ecological and socio-economic requirements (Sims & 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 agro-ecological and socio-economic 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).

The paper proceeds as follows. In section 2, 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 section 3, the authors present some of the key debates on the advantages and disadvantages of animal traction, two-wheel tractors, and four-wheel tractors. In section 4, the authors present and apply the conceptual “best fit” framework, which can help to guide policymakers and development partners investing in farm mechanization. Section 5 discusses and concludes the paper.

2. 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. In the following paragraphs, trends related to each of the three technological pathways will be shown:

- **Animal traction:** Across Africa, 15% of the farmland is estimated to be cultivated using animal traction (FAO & AUC, 2018). These continent-wide averages mask high heterogeneity. Northern Africa has a long tradition in the use of draught animals, potentially facilitating the adoption of tractors, which are currently replacing draught animals (Starkey, 2000). In the Horn of Africa, e.g. in Ethiopia and Eritrea, the animal-drawn *Maresha* plow is used for around 3000 years (Gebregziabher et al., 2006; Starkey, 2000; Takele & Selassie, 2018). 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 earlier state-led tractorization programs and the fossil fuel crisis (Mrema et al., 2008; Starkey, 2000; Wilson, 2003). Efforts to promote draught animals were successful in some Western African countries (e.g. Burkina Faso, Mali) 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 & Polson, 1993; Havard et al., 2000; Starkey, 2000). Today, adoption rates vary widely across Africa. In Ethiopia, the share of farmers using draught animals is still estimated to be between 60% and 80% (Berhane et al.; 2020; Sheahan & Barrett, 2018). This share is estimated to be around 25% in Tanzania and Nigeria (Mrema et al., 2020; Takeshima & Lawal, 2020; Sheahan & Barrett, 2018). In Mozambique, around 10% of the farmers use animal traction (Cabral, 2022). Adoption rates are close to zero in much of Central Africa where disease undermine the use of animal traction (Alsan, 2015; Mrema et al., 2008; Pingali et al., 1987). While animal traction is widespread and on the rise in some parts of Africa (Diao et al., 2020; Sims & 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 draught-resilience animals (Ellis-Jones et al., 2005; Starkey, 2000). Draughts 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 & Kienzle, 2008; Starkey, 2000).

- **Four-wheel tractors:** Across Africa, 5% of the farmland area is estimated to be cultivated with tractors but there are large variations across the continent (FAO & AUC, 2018). Tractor use is high in Northern Africa and South Africa. Kirui (2019) estimates that up to 60% of the farmers in Egypt and up to 70% of the farmers in South Africa use tractors. In Sub-Saharan Africa, tractor use is much lower. 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 & Birner, 2017; Pingali et al., 1987; Pingali, 2007; FAO & AUC, 2018; Mrema et al., 2008). More recently, some African governments again set up public mechanization programs but there are again signs of failure (Daum & 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 (Daum & Birner, 2020; Diao et al., 2020; FAO & AUC, 2018). Today, tractor use rates vary widely across and within the countries of Sub-Saharan Africa. In Ghana, around one-third of the farmers use tractors – ranging 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 Tanzania, around 14% of the farmland is cultivated with tractors, mainly in large-scale commercial farming areas (Mrema et al., 2020). In Nigeria, 7% of the farmers use tractors (Takeshima & Lawal, 2020). In other countries, the use of tractors is “extremely low” (Mrema et al., 2008), often around 1% such as in Burkina Faso, Cameroon, Ethiopia; Malawi, Mozambique, Niger, Senegal, Uganda (Berhane et al., 2020; Cabral, 2020; Kirui, 2019; Sheahan & Barrett, 2018).

- **Two-wheel tractors:** There are no Africa-wide statistics for the use of two-wheel tractors but country case studies provide some insights. Overall, African tractorization is heavily dominated by four-wheel tractors and two-wheel tractors only play a role in some countries and farming systems (Diao et al., 2020; Mrema et al., 2018). 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 towards 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 many efforts to promote animal traction and four-wheel tractors, efforts to promote two-wheel tractors struggled because of a lack of economic demand at the time. Today, manufacturers in particular from Asia are trying to supply two-wheel tractors across much of Africa but significant adoption has taken place in only a few countries – i.e. 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 9,000 between 2005 and 2015 – for comparison, there are around 13,000 four-wheel tractors (Mrema 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 oxen that were used as draft animals (Mrema et al., 2020). In Ethiopia, there are estimated to be around 4000 two-wheel tractors (Baudron et al., 2015), of which three quarters were publically procured (Kahan et al., 2018). Data from one of Ethiopia’s largest agricultural machinery dealer reveals 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 (Berhane et al., 2020), however, it is reported that their adoption is gaining momentum as they were promoted as part of the FACASI project between 2014 and 2017 (FACSI, 2019). In Nigeria, one of the largest markets for farm mechanization, two-wheel tractors play only a very limited role (Takeshima & 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).

3. 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 towards the use of four-wheel tractors. Figure 1 shows these different technological trajectories. Each of these debates will be presented in detail in the next sections.

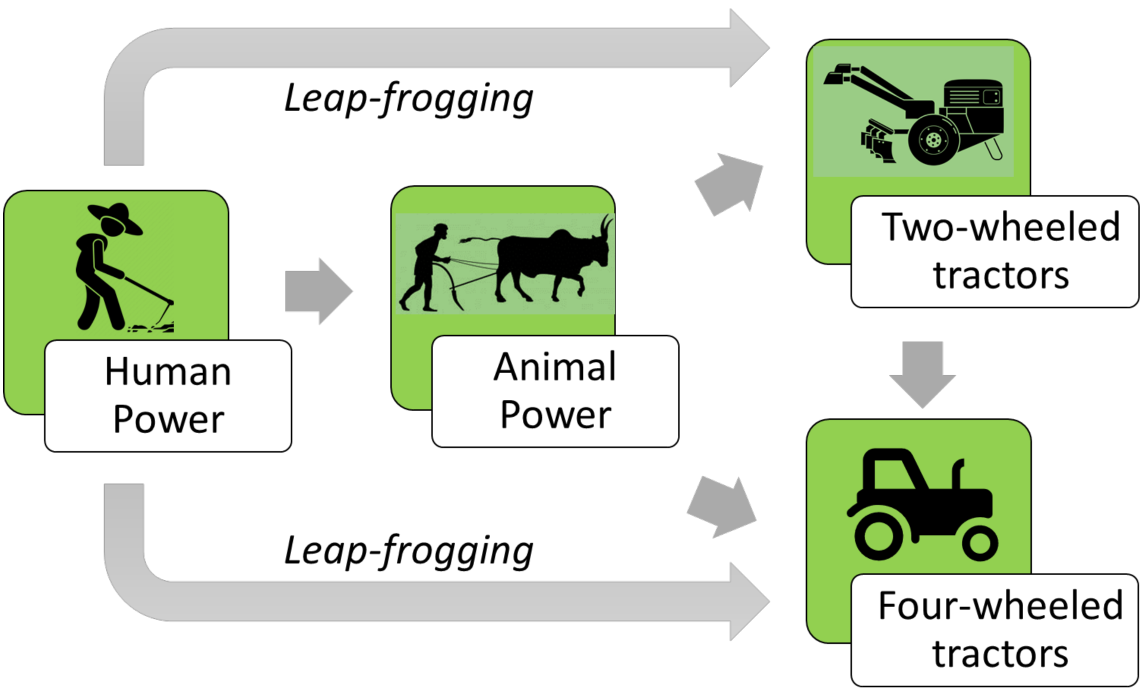


Figure 1. Technological pathways in farm mechanization

Source: Authors

3.1. 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 (Sims & Kienzle, 2006) as well as the lower labor use and drudgery as compared to animal traction (Daum & Birner, 2021; Sims & Kienzle, 2006). Sims & 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 draughts animals outside of the farming season (Ehui & Polson, 1993; Mrema et al., 2008; Sims & 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" (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 for 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 & 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; Mrema et al., 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 & Kolavalli, 2013; Thierfelder, 2021). While draft 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 & Polson, 1993; Ellis-Jones et al., 2005; Pearson and Vall, 1998; Sims & Kienzle, 2006; Wilson, 2003). For the majority of African smallholder farmers using animal draft power would already mean progress. Animal traction is argued to be more affordable and suitable for smallholder farmers (Ellis-Jones et al., 2005; Starkey, 2000; Takele & Selassie, 2018; Tefera, 2011; Pingali et al., 1987; Pearson and Vall, 1998). 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 & 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 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 & Selassie, 2018).

Owning draught animals as compared to hiring tractors may come with additional advantages for farmers. Farmers can use the animals to build up capital, 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 & Vall, 1998; Tefera, 2011; Wilson, 2003). 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). 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.

3.2. 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 & 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; Baudron et al. 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; Daum et al., 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 & 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 offer spare parts and repair services for two-wheeled tractors due to its simple single cylinder engine – whereas owners of four-wheel tractors have to travel larger distances to find skills 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 many 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 the timeliness and are more energy- and labor-saving than two-wheel tractors (Baudron et al., 2015; Daum & Birner, 2017). Moreover, four-wheel tractors are argued to have an advantage over two-wheel tractors as the latter are still associated with heavy physical work – often under hot conditions and in direct sunlight without out without shade (Daum & 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 & 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, 2022; 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.

4. Best-fit framework to guide farm mechanization

Table 1 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 a land preparation. The framework is based on the understanding that the comparative advantage of the three technological pathways depends on agro-ecological and socio-economic factors (termed layers in Table 1). 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 but some can be changed (e.g., trees, stumps, and stones can be removed). 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.

Layers	Dimension	Characteristics			
Agro-ecological	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*		*Wetland*	
	Topology	*Flat*		*Hilly*	
	Trees, stumps, 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*	
Socio-economic	Farm sizes	*Small*		*Large*	
	Labor costs	*Low*		*High*	
	Energy costs	*Low*		*High*	

Table 2. Agroecological and socioeconomic dimensions affecting farm mechanization

Source: Authors

Table 2 shows the comparative advantages and disadvantages of the three technological pathways (animal traction, two-wheel tractors, and four-wheel tractors) across all agro-ecological and socio-economic dimensions, which allows assessing which of the three technology options "best fits" the respective characteristics. In Table 3, comparative advantages are marked in dark green and comparative disadvantages are marked in yellow. Light green colors signal where 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 2). Two-wheel tractors also have a comparative advantage where farms are small and fragmented (see Table 2). Two-wheel tractors have a comparative advantage over animal traction in arid and semi-arid agro-ecological 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 2). 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 2). In the subsection sections, the comparative advantages and disadvantages of the three technological options concerning all agro-ecological and socio-economic dimensions are discussed based on the available empirical evidence.

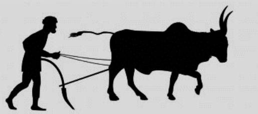
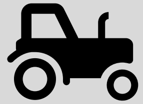
Layers	Dimension	The comparative advantage of three technological pathways											
		Animal traction 				**Two-wheel tractors** 				**Four-wheel tractors** 			
Agro-ecological	Farming system evolution	*Forest fallow*	*Bush fallow*	*Grass fallow*	*Annual Cultivation*	*Forest fallow*	*Bush fallow*	*Grass fallow*	*Annual Cultivation*	*Forest fallow*	*Bush fallow*	*Grass fallow*	*Annual Cultivation*
	Agro-ecological zone	*Arid*	*Semi-Arid*	*Semi-Humid*	*Humid*	*Arid*	*Semi-Arid*	*Semi-Humid*	*Humid*	*Arid*	*Semi-Arid*	*Semi-Humid*	*Humid*
	Soil texture	*Light*		*Heavy*		*Light*		*Heavy*		*Light*		*Heavy*	
	Production type	*Dryland*		*Wetland*		*Dryland*		*Wetland*		*Dryland*		*Wetland*	
	Topology	*Flat*		*Hilly*		*Flat*		*Hilly*		*Flat*		*Hilly*	
	Trees, stumps, stones	*Low*		*High*		*Low*		*High*		*Low*		*High*	
	Mixed farming (crop-livestock)	*No*		*Yes*		*No*		*Yes*		*No*		*Yes*	
	Pasture, fodder, water availability	*Low*		*High*		*Low*		*High*		*Low*		*High*	
	Animal diseases prevalence	*Low*		*High*		*Low*		*High*		*Low*		*High*	
	Heat and humidity stress	*Low*		*High*		*Low*		*High*		*Low*		*High*	
Socio-economic	Farm sizes	*Small*		*Large*		*Small*		*Large*		*Small*		*Large*	
	Labor costs	*Low*		*High*		*Low*		*High*		*Low*		*High*	
	Energy costs	*Low*		*High*		*Low*		*High*		*Low*		*High*	

Table 2. Best-fit framework to guide farm mechanization

Source: Authors

Legend: Comparative Advantage | Neutral | Comparative Disadvantage

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 & 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 & Polson, 1993; Havard & 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 & 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) towards annual and later multiple cultivation (Boserup, 1965; Ruthenberg, 1980). This shift entails an intensification of farm production and comes with rising labor requirements per hectare of cultivated land (Ehui & Polson, 1993; Ruthenberg, 1980; Pingali & 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 & Polson, 1993; Havard & Le Thiec, 1999; Pingali & Binswanger, 1984). At the same time, de-stumping costs decline (Ehui & 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 & Selassie, 2018). Farmers may start to cultivate fodder crops but this typically raises the costs of feeding animals and is very labor-intensive (Ehui & 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 & Kienzle, 2006). Crops residues may also be used but they are of lower nutritional value unless combined with supplements (Sims & 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 with 100. According to Ruthenberg (1980), animal traction typically evolves with R-values 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 & 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 towards the use of tractors (Diao et al., 2020).

Figure 2 indicated in brown-red colors where shifting cultivation was practiced during the 1960s and 1970s but where farmers now practice annual cropping. Figure 2 also shows in yellow colors where shifting cultivation was still practiced during the 2010s. In these areas, farmers may still use hand labor or else animal traction can have a comparative advantage over the use of tractors. Figure 3 also shows that annual cultivation is now practiced in many parts of Africa, however, there are still also parts where extensive fallow periods are possible.

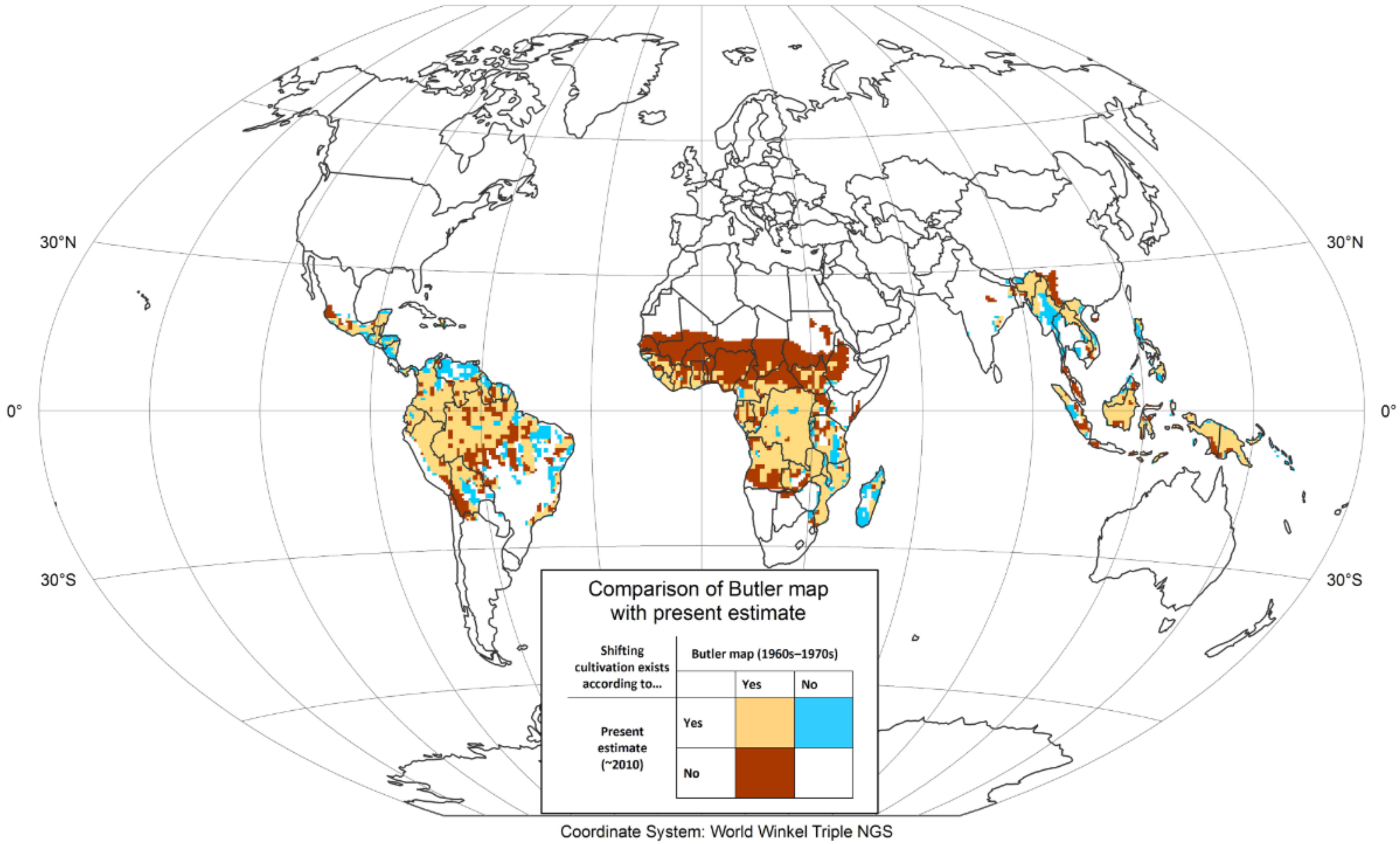


Figure 2. Shifting Cultivation in 2010

Source: Heinimann et al. (2017)

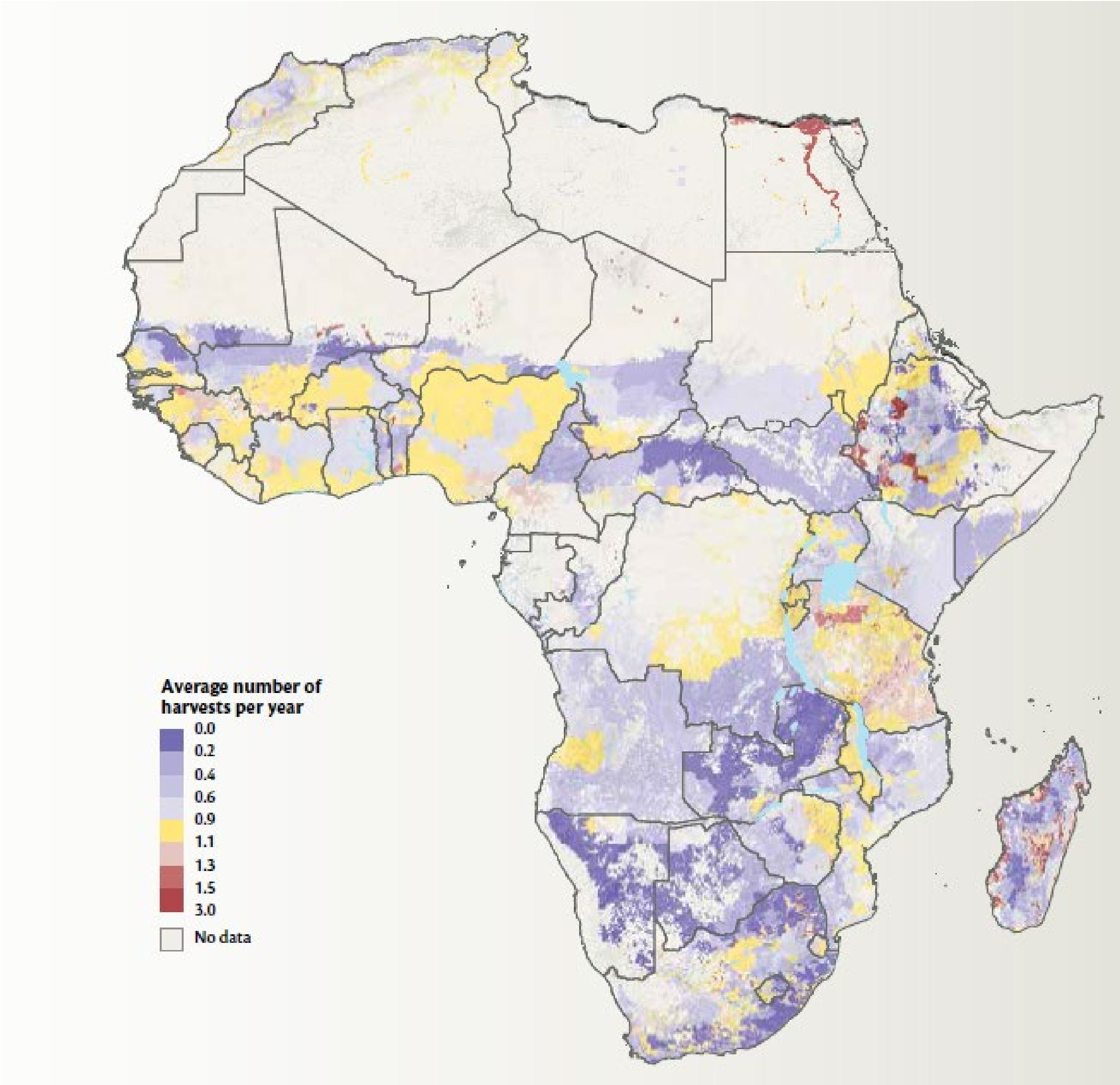


Figure 3. The average number of harvests per year

Source: Sebastian (2014)

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 to 270 days; and in humid areas, the growing period can last longer than 270 days. Figure 4 provides an overview of agro-ecological 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 draft animals (including during the extended off-farm season) outweigh the benefits (Baudron et al. 2015; Mrema et al., 2020; Pearson and Vall, 1998; Sims & 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; Pingali et al., 1987; Mrema et al., 2008) 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 & Kienzle, 2006). Tractor service markets are also affected by similar synchronicity and seasonality problems (Mrema et al., 2008; Sims & 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 explains why animal traction is mostly concentrated in semi-arid and sub-humid areas of Africa (Havard et al., 2000; Havard & Le Thiec, 1999; Pearson and Vall, 1998; Williams, 1997) – as well as in high-altitude regions (Havard & Le Thiec, 1999). Pingali et al. (1987) has 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 draft 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 & 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, paddyrice 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 & 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 & Kienzle, 2006). This changes at the edges of the humid zone, where forage opportunities are higher and health risks are lower (Havard & Le Thiec, 1999).

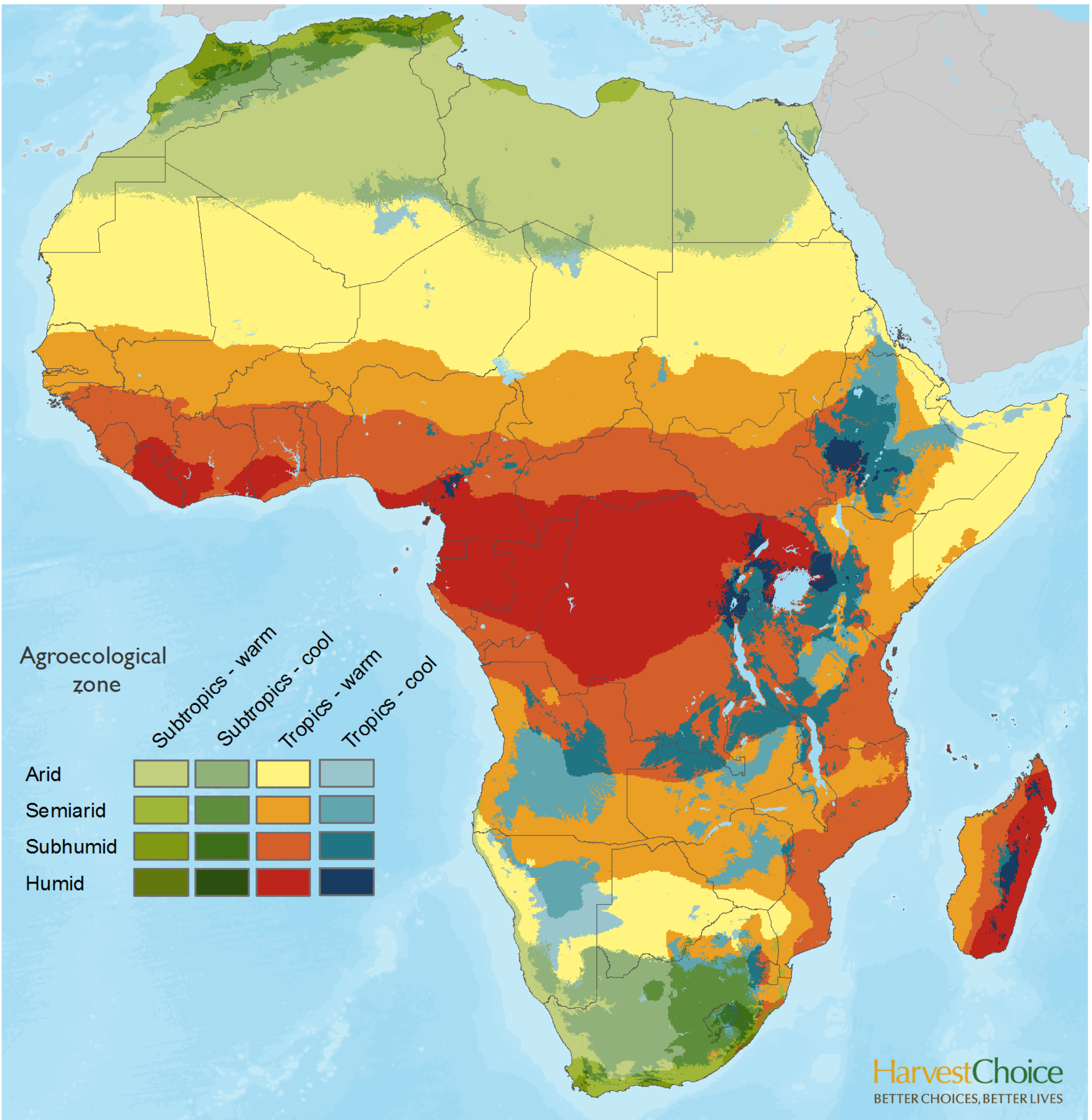


Figure 4. Agroecological Zones in Africa

Source: Sebatian (2009)

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).[1] 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 & 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 & Getnet, 2016). Kahan et al. (2018) has argued that "land preparation and tillage are more effectively conducted by ploughing with 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 Figure 5). 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 soil (e.g. silt and clay soils), which are common in more humid areas, more farm power is needed for land preparation (Binswanger & Donovan, 1987). On such soil, plowing with draft animals is very difficult under dry conditions (Stout & 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, e.g. in heavy and moist vertisols (Baudron et al., 2015; Baudron et al., 2019b; Kahan et al., 2017). Hence tractors are more likely to have a comparative advantage (Binswanger and Donovan, 1987). In Nigeria, Takeshima & 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 draft power is mainly used for control-intensive operations (Tadesse et al., 2019).

[1] 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).

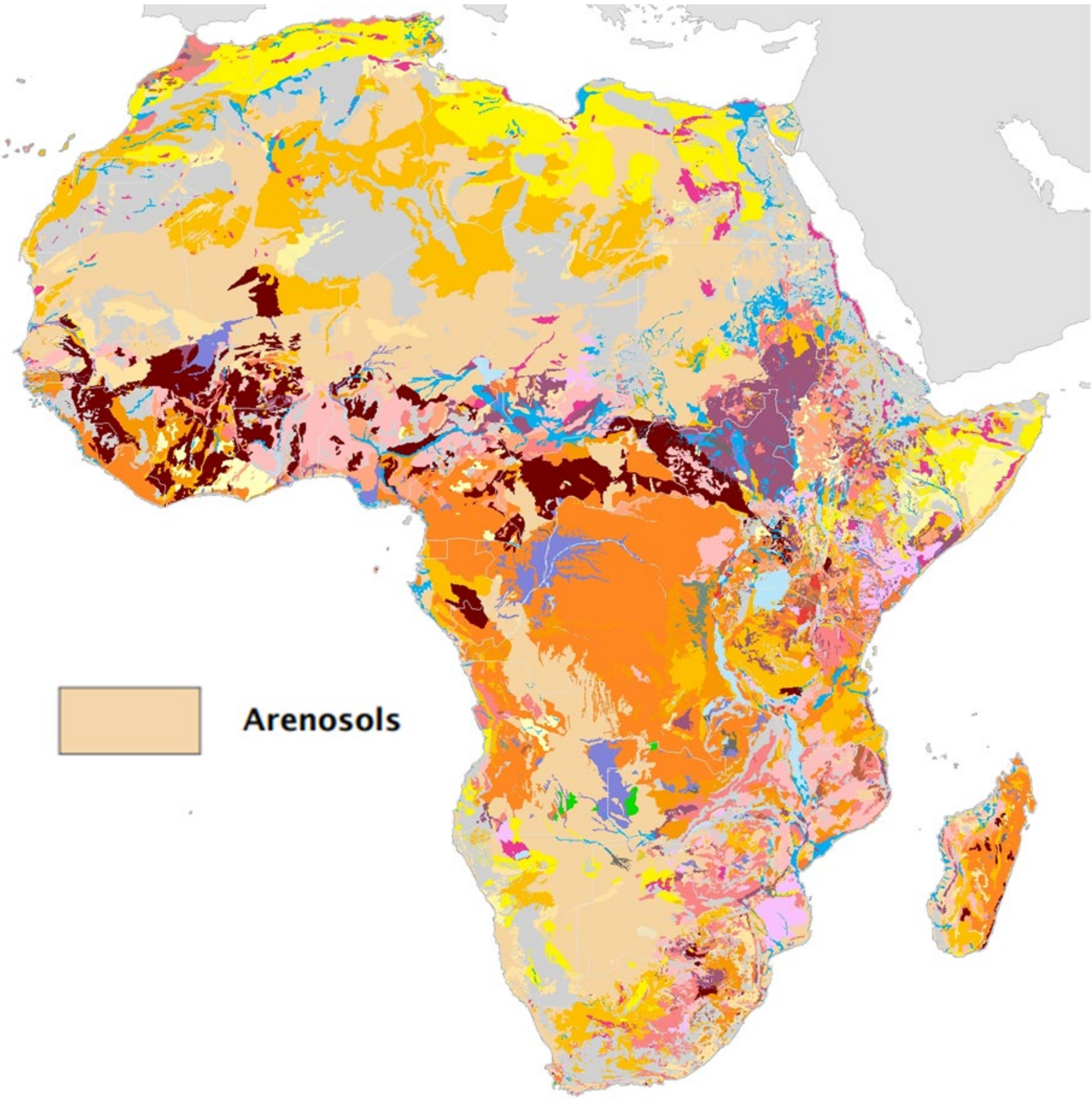


Figure 5. Soils Types in Africa (Arenosols)

Source: Jones et al. (2013)

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; Baudron et al., 2019b; Sims & 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 & Polson, 1993; Sims & Kienzle, 2006).

Conservation Agriculture also eases the workload for draught animals. Baudron et al. (2015) also see a 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 timeliness of tillage and planting operations with animal drawn ripping tillage in the 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: wetland versus dryland

Wetland versus dryland cultivation matters insofar as two-wheel tractors have a unique comparative advantage in wetland 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; Mrema et al., 2020). In such systems, draught animals can also have a comparative advantage. For example, they are used in the irrigated fields along the Nile (Starkey, 2000) and irrigated fields in Ethiopia (Tafera, 2011). Baudron et al. (2015) have argued that two-wheel 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 the previous section on "Soil texture").

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) has 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 & Le Thiec, 1999). Also, the performance of some 2WT may decreases in higher altitudes due to low oxygen for combustion, which is in contrast to 4WTs which are typically equipped with with high altitude compensator devices.

Trees, stumps, and stones

The prevalence of trees, stumps, and stones can also shape mechanization trajectories (Berhane et al., 2020; Daum & Birner, 2017). In general, tree-based farming systems are more difficult to mechanize (Cramb & 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; Baudron et al. 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 the field with trees (Baudron et al., 2015). Where farmers want to use tractors, substantial investments in de-stumping are needed to avoid costly breakdowns (Pingali et al., 1987; Diao et al., 2018). Next to trees and tree stumps, stones are another challenge. 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 2WT or 4WT tractors but 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”. 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”. Pingali et al. (1987) has 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 draft power” (p. 122).

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 towards motorized mechanization (Baudron et al., 2015; Binswanger-Mkhize & Savastano, 2017; Diao et al., 2020; Ehui & Polson, 1993; Ruthenberg, 1980; Pingali & 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 & Selassie, 2018). Another reason is that the demand for meat is increasing, affecting the costs of oxen (Birhanu, 2019; Henchion et al., 2021). Kahan et al. (2018) has argued that “2WTs may make in roads 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 bodiesin many areas in Africa (Ellis-Jones et al., 2005). In Ghana, lacking access to feed during the dry season increasingly constraints animal traction (Houssou & Kolavalli, 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 draft 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”. 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).

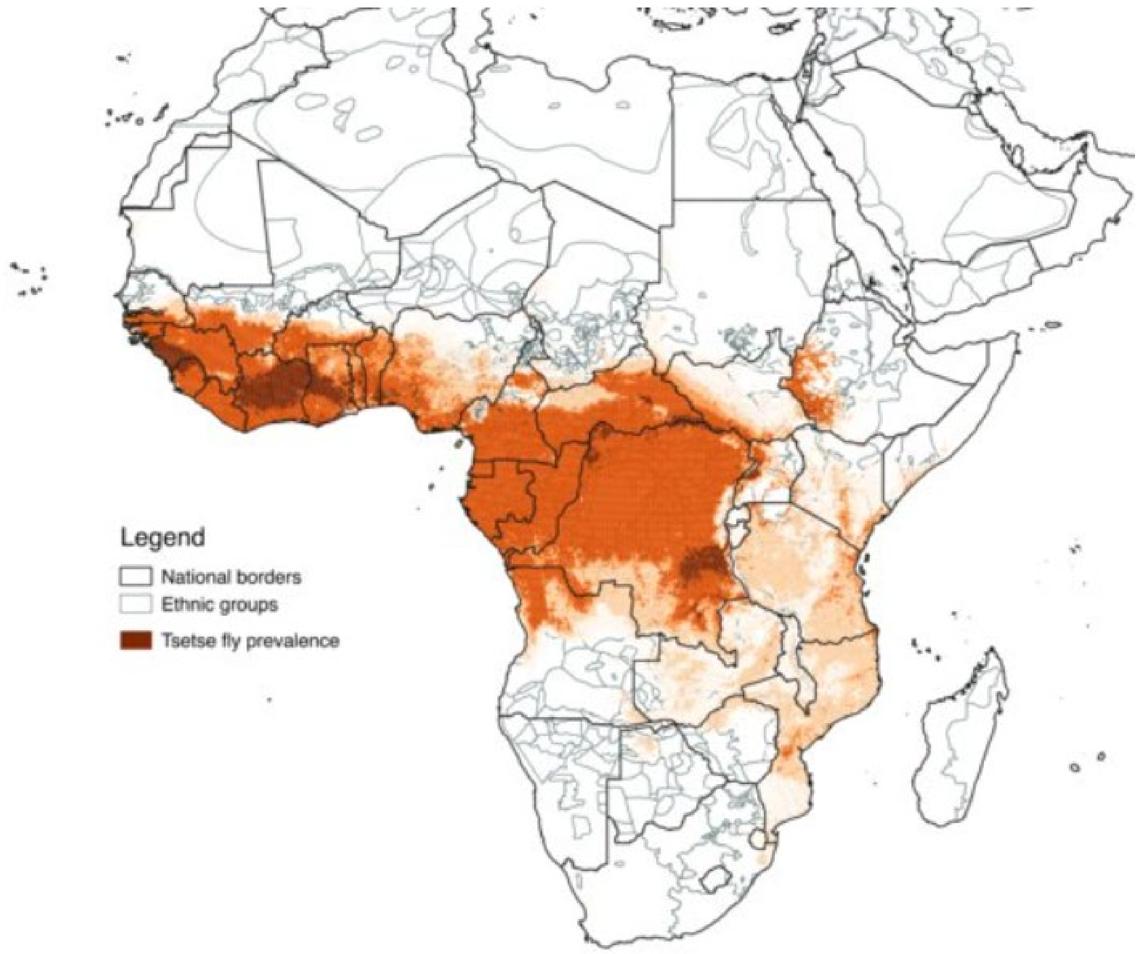


Figure 6. Tsetse fly distribution in Sub-Saharan-Africa

Source: Schaub (2017)

In forested and humid parts of Africa, tsetse flies are common, a vector of animal diseases such as trypanosomiasis (Sims & 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 & 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 & 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 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 makes animal susceptible to animal disease (Wilson, 2003).

Temperature and humidity stress not only affects animal traction but also the 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 and arduous ergonomically" (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 the 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 economics of scale as compared to tractors. Sims & Kienzle (2005) 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") 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 section 3.2.), and that there are also small horsepower tractors (category 1 tractors) that similar in size as compared to two-wheel tractors.

Figure 7 shows 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 wheels tractors) have a comparative advantage. It is important to keep in mind that four-wheel tractors can also vary in power and size.

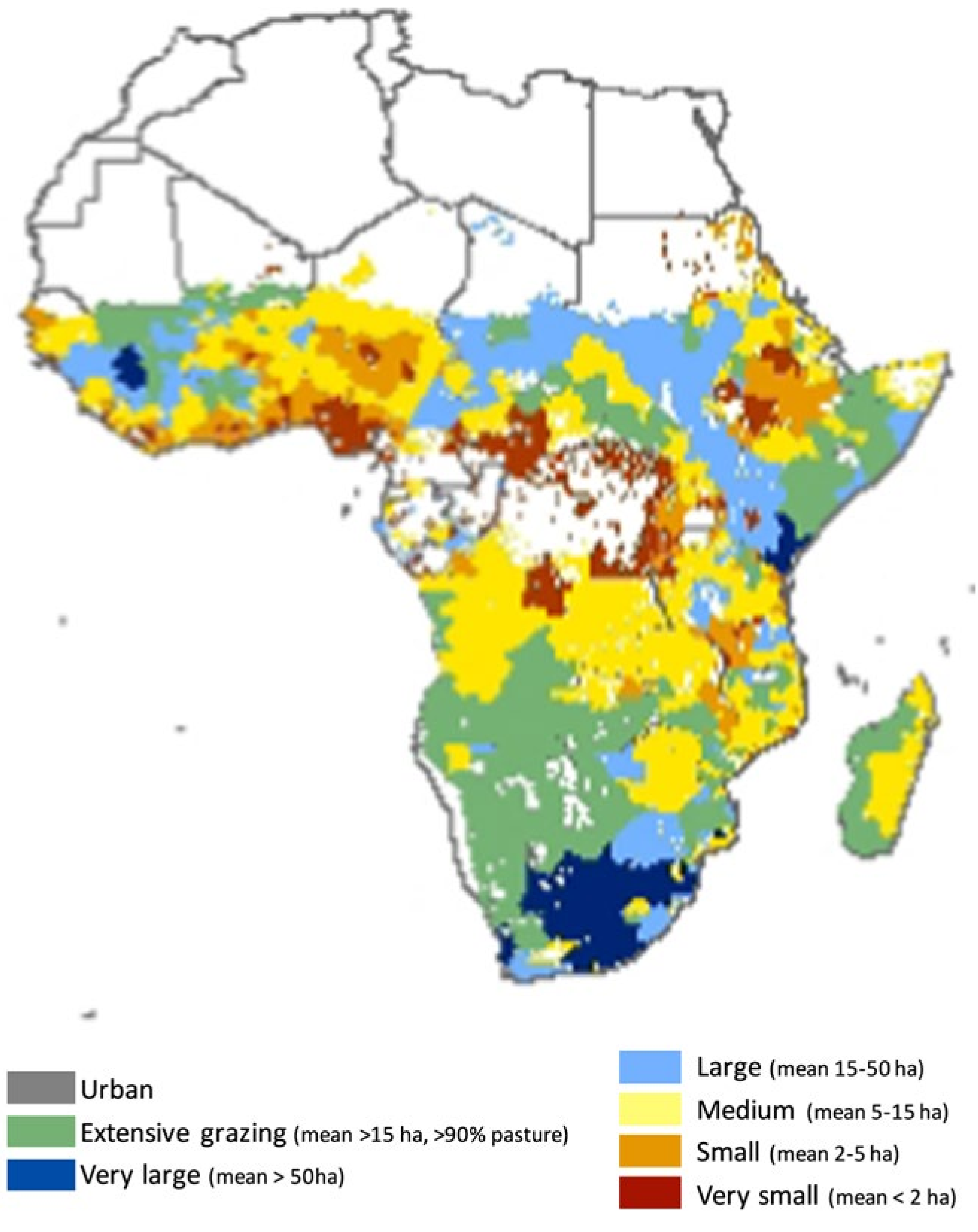


Figure 7. Average farm sizes in Sub-Saharan-Africa

Source: Samberg et al. (2016)

Institutional solutions for smallholder mechanization such as asset-sharing arrangements can reduce the comparative disadvantage of four-wheel tractors where farms a small and fragmented to a certain degree and but setting up such arrangements can be hampered by several challenges. For one, mechanization service markets are also more difficult to set up where farmers have small and fragmented plots as this raises transaction costs (Daum

& Birner, 2017; Daum et al., 2021; Sims & 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, 2022; 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 & Kienzle (2016) show animal traction can reduce the workload associated from around 500 labor hours per hectare to only 60 hours – however, tractors need only one to two 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 involves 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 & Polson, 1993; Wilson, 2003). Moreover, unlike tractors, draught animals have to be trained (Wilson, 2003). The higher labor use for using draft 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 & Polson, 1993; Wilson, 2003). In Ghana, Houssou & Kolavalli (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, 2022; Diao et al., 2020; Sims & 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 comparate 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 & 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) has argued that (two-wheel) tractors only have 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 “price of fuel and availability of regular supplies bears directly on the profitability of using mechanical power sources in agriculture” (p. 39).

5. 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 agro-ecological and socio-economic 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; Baudron et al., 2019b) and the scope for four-wheel tractors widens where affordable and reliable asset-sharing arrangments 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 & Anamor, 2021; Daum & Birner, 2017; Takeshima & 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 agro-ecological and socio-economic 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 agro-ecological and socio-economic factors are likely to fail in their efforts, as the history of farm mechanization in Africa has shown (Pingali et al., 1987; Sims & Kienzle, 2006). Hence, policies and investments towards farm mechanization should be guided by agro-ecological and socio-economic frame conditions (see also Mrema et al., 2008) and not political considerations such as an appeal of large "modern" tractors (Cabral, 2022; Cabral & Amanor, 2021). This applies in particular to the role of animal traction, which continues to have a comparative advantage in parts of Africa, but tends to be neglected by policymakers due to its image as being "archaic and antiquated" (Daum and Birner, 2017; Daum et al., 2022; Starkey, 2000; Wilson, 2003, p.21). Starkey (2000) has long argued that animal traction would be more widespread was it not for competing subsidies and legislation.

The "best-fit" framework highlights which agroecological and socio-economic 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 on which farm mechanization pathway "best-fit" 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 should be prioritized and supported 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 Organisation (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 (Sims & Kienzle, 2006; FAO & AUC, 2018). Assessing both the present and likely future situation is important due to technological advancements, as some agro-ecological and socio-economic factors can change quickly, and as setting up sound enabling environments take 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 & Kienzle, 2006). However, it is important to keep in mind that farmers' decision-making is not always "rational", e.g., they may find large tractors more attractive than small ones due to status considerations, and that farmers of different gender may have different mechanization needs and preferences.

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 disadvanteges of the three mechanization solutions mainly regarding on-farm activivities (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 section 3.1.) and the multifunctionality of two-wheel tractors (see section 3.2.), which are important to consider, however. When applying the "best-fit" framework at the county-levels it is also important to keep in mind that the sizes of four-wheel tractors vary significantly (see section 3.2.).

All three pathways hinge on public support (Daum & 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 towards 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 towards obtaining more powerful and more disease-tolerant and drought-resistant draught animals and with 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 set up 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.

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 agro-ecological and socio-economic conditions.

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