Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheel tractors, conservation agriculture, and private sector involvement

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Abstract

The need for sustainable intensification in sub-Saharan Africa (SSA) is widely recognized, in order to achieve food security with minimum negative social and environmental consequences. In current Research & Development programs, much emphasis is placed on increasing the efficiency with which land, water and nutrients are used, whereas farm power appears to be a ‘forgotten resource’. This is a major concern when farm power in SSA countries is declining due to the collapse of most tractor hire schemes, the decline in number of draught animals and the growing shortage of human labour. A consequence of low farm mechanization is high labour drudgery, which makes farming unattractive to the youth and affects women disproportionally. Undoubtedly, sustainable intensification in SSA will require an improvement in the farm power balance. In this paper, we suggest this can be achieved through the use of small, multipurpose and inexpensive sources of power such as two-wheel tractors (2WTs) coupled with the promotion of energy saving technologies such as conservation agriculture (CA), whilst ensuring the profitability for farmers, service providers and other private sector actors in the supply chain. We argue that appropriate mechanization in Africa, a paradigm abandoned three decades ago, may be re-examined through the combination of these three elements.

Key words: power tiller, drudgery, intensification

The promotion of large-scale mechanization in sub-Saharan Africa (SSA) in the 1950s and 1960s raised concerns over possible undesirable consequences of such forms of mechanization (e.g. labour displacement, consolidation of small farms) and led to the emergence of what has been coined ‘appropriate’ mechanization in the 1970s and 1980s (Mrema et al., 2008). However, none of the small machines that were developed during that period – including a number of ‘mini-tractors’ – were successful in the market (Holtkamp and Lorenz, 1990). More than twenty years after the apparent failure of appropriate mechanization in Africa, this paper proposes to re-examine the topic in the context of modern day developments in the agricultural sector.

1. Increasing food production in SSA will require an increase in available farm power

Although food production in SSA is increasing, population growth in the region outstrips food supply (ca. 3% vs. ca. 2%, Tittonell and Giller, 2013; Figure 1a). The gap between food demand and food supply is not being met through trade, as demonstrated by the steady rise of undernourished people in SSA in the past decades (FAO, 2009; Figure 1b). In addition, relying on trade exposes SSA countries to food price volatility (Abbott and de Battisti, 2009). In 2007-08, peaks in international grain prices were transmitted to domestic food markets in SSA, eroding the purchasing power of urban and rural households (Minot, 2011) and sparking food riots in several countries (Berazneva and Lee, 2013). Notwithstanding the importance of global and regional trade, a concerted effort is needed to enhance agricultural production and productivity in SSA to address the region’s food security concerns. As noted by Clarke and Bishop (2002), an increase in agricultural output usually requires additional power.

However, SSA farmers are not only under pressure to produce more: they also have to produce differently. Whereas the rural population of SSA has increased at an average rate of 2% per annum between 1968 and 2000, the urban population has increased at an average rate of 5% per annum during the same period (Tiffen, 2003). As a result, consumers of agricultural products are increasingly urban (Figure 1c). This demographic shift has two implications for SSA farmers: a change in demand for agricultural commodities, for example for more milled and polished grains (Popkin and Bisgrove, 1988), and greater need for transport from the farms to the centres of demand (Tiffen, 2003). More processing and more transport to satisfy urban demand obviously require more power.

Thus, the need by SSA farmers for more production, processing and transport is increasing farm power demands. In the next section, the trend in farm power in SSA is examined.

2. Could farm power be one of the most limiting factors in many farming systems of SSA?

The tremendous increase in the value added by agriculture, particularly over the past decade (Figure 1d), has made investment in agricultural inputs such as mineral fertilizers possible, in countries such as Ethiopia and Kenya. However, in contrast with other countries that experienced the Green Revolution (e.g. India), the farm power available per area of agricultural land in SSA has been stagnating over the past three decades (Figure 2). In many countries, the number of (four-wheel) tractors in 2000 was identical (e.g. Malawi) or even lower (e.g. Tanzania) than in 1980 (Figure 2a). In others, the number of (four-wheel) tractors has increased from 1980 to 2000, but not at a rate commensurate with the increase in agricultural land area (e.g. Zimbabwe). During the same period, the number of draught animals on the African continent has stagnated, or even declined, because of feed shortage, droughts, and diseases (Figure 2b). As a result, agriculture in SSA increasingly relies on human muscle power. Although labour availability has increased in many countries - with the number of economically active people in agriculture increasing faster than the cultivated area (e.g. Kenya, Tanzania) - it has decreased in others (e.g. Zimbabwe; Figure 2c).

The quality of labour has also deteriorated in most of SSA as a result of an ageing population (stemming from rural-urban migration, Table 1) and HIV/AIDS (Table 2). Female headed households are also quite common in SSA and are particularly labour constrained (Table 2). Rural families in SSA also rely in part on non-farm income. This is particularly the case of poorer households and of small farms in semi-arid areas, where income diversification is a strategy to spread risk (Tiffen, 2003; Figure 3). These non-farm activities may compete with on-farm activities. High labour drudgery that characterizes on-farm activities in SSA, as a consequence of low farm mechanization, may result in household members – and particularly the youth exposed to alternative urban livelihoods – favouring non-farm over on-farm activities (Diao et al., 2012).

Thus, following the analysis above, we argue that farm power (quantity and quality) represents a major limiting factor on productivity in many farming systems of SSA. Supporting evidence exists to illustrate the link between farm power and farm productivity. In areas of low population density, farming is often limited more by labour and draught power than by land (Baudron et al., 2012). For example, the quantity of cereals produced by farming households in the Ethiopian Rift Valley increases with increasing numbers of draught animals owned by these households (Baudron et al., 2014; Figure 4a). Farm production may be affected by power constraints in more subtle ways, including low nutrient input and delayed planting. Manure is often the main source of nutrients applied to fields in SSA. However, manure is a bulky material that requires labour and/or draught power for its transport and application (Tittonell et al., 2005). As most farming households experience constraints in their available farm power, they tend to apply most of the manure available to the fields closest to the homestead (Zingore et al., 2007; Figure 4b). As a result of negative nutrient balances, fields further away may become degraded and unproductive (Tittonell and Giller, 2013). Constraints in farm power may also result in delayed land preparation and delayed planting, which often result in severe yield penalties in SSA (Figure 4c).

Evidently, agricultural production in SSA is unlikely to increase without addressing the issue of limited farm power availability, particularly during labour peaks, which tend to be more pronounced for the poorer farming households (Figure 4d). However, the emphasis of current agricultural research and development in the region is on seeds, nutrients and water (http://simlesa.cimmyt.org/; http://africa-rising.net/; http://www.agra.org/), whilst farm power appears as the 'forgotten resource'. The lack of concern for farm power and mechanization in SSA can also been seen by the paucity of literature on the topic since the 1990s (Diao et al., 2012). In the past decades, departments of agricultural engineering in international universities and research organizations have also faced severe declines in resources, and even closure (Biggs et al., 2011).

Below, we propose a new approach to farm mechanization in SSA, which we argue is a necessary condition for food security in the region.

3. Addressing the issue of declining farm power

3.1. Increasing power supply through appropriate mechanization

Farm power constraints may be alleviated by increasing the power supply (i.e. agricultural mechanization) or by decreasing power demand (i.e. power-saving cropping systems). Diao et al. (2012) have proposed three stylized supply models of agricultural mechanization, based on the experiences of some Asian countries in which – similarly to SSA - smallholders dominate. These models are typified by India (where medium to large scale farmers own medium-size machines and hire out their services to other farmers), China (where specialized enterprises migrate over large areas), and Bangladesh (where small-scale farmers own small machines and hire out their services to other farmers).

The Indian model is based on high public support in the form of subsidies – for the purchase of four-wheel tractors (4WTs) and other machines – marketing regulations (such as minimum price guarantee), and large investment in infrastructure (Singh, 2006; Hazell, 2009). This level of public support is currently unlikely to occur in most of SSA due to fiscal limitations. Moreover, this model has resulted in large inequities, favoring medium- to large-scale farmers and leaving many of the small-scale farmers without access to mechanization (Biggs et al., 2011). These inequalities play out through large regional disparities, with Punjab and Haryana having the highest levels of mechanization and the Eastern states (e.g. Bihar, Orissa) the lowest (Singh, 2006).

The Chinese model is based on migration of specialized equipment like combine harvesters and thus requires a high quality rural road network, which is absent in many SSA countries. Moreover, this model requires large ('subcontinental') agroecological areas with rainfall gradients, whereas SSA is fragmented into relatively small farming regions and/or countries (Dixon et al., 2001).

The authors feel the third model - the Bangladeshi model - is more applicable and can be adapted to large parts of SSA. This model may also describe mechanization processes in several South and South East Asia countries such as Thailand, Vietnam, or Sri Lanka. Bangladesh's agriculture, which relies on small machines such as two-wheel tractors (2WTs), is one of the most mechanized of South Asia, far more than India's agriculture, which relies on larger machines: ~80% of the cropland of Bangladesh is prepared mechanically, against less than ~50%% in India (Kulkarni, 2009; MTD, 2013). Even though all farmers, even the poorest, have access to 2WTs, only about one in thirty farmers actually owns one (Justice and Biggs, 2013). This means that nearly every 2WT owner is a service provider, and that the large majority of 2WT users gain access to mechanization by hiring service providers. This model of mechanization appears equitable as even the poorest farmers have access to 2WT-based services, which are cheaper than services using animal traction or 4WTs (Alam, 2003; Roy and Singh, 2008). This is made possible by the low cost of 2WTs – making their purchase possible for many farmers without support of a formal financial institution – and the use of the 2WT for multiple purposes including transport, post-harvest operations and water pumping that leads to high annual rate of return on investment (Biggs et al., 2011; Diao et al., 2012).

This form of appropriate mechanization has been possible thanks to the removal of duties, sales taxes and standardization restrictions on low horsepower diesel pumps and 2WTs in 1988 (Biggs et al., 2011). These policy changes stimulated the emergence of a private-sector led supply chain for mechanization guaranteeing that the specifications and the price of the machines imported matched local demand (Diao et al., 2012). The private sector – which is guided by profitability – is better equipped than the public sector to understand this demand, and in particular the trade-offs that exist between machine quality and machine cost. Although Japanese and Korean 2WTs are of superior quality compared to Chinese 2WTs, their price is more than double. As a result of a demand for cheap and 'good enough' 2WTs, the 2WT market in Bangladesh is largely dominated by Chinese 2WTs (Biggs et al., 2011).

3.2. Decreasing power demand through power saving technologies

Land preparation is the most energy-demanding farming operation in rainfed agriculture (Lal, 2004). Simplification of this operation – i.e. using reduced or no tillage – leads to a major reduction of power demand for farming. Although this depends on soil properties (e.g. texture, moisture), reduced or no tillage cuts energy requirements by about half compared to conventional land preparation i.e. mouldboard or disc ploughing (Lal, 2004). Thus, it could be argued that the elimination of soil inversion makes the use of low powered, affordable and easy to maintain 2WTs a viable option for rainfed agriculture. It is well recognized that 2WTs can only produce enough traction to plough wet paddy fields, but not dry soils in rainfed conditions (Holtkamp and Lorenz, 1990; Singh, 2006). Therefore, reduced or no tillage could make the use of 2WTs viable under rainfed conditions. Moreover, although 2WTs have a lower field capacity than larger 4WTs, reduced or no tillage is faster compared to conventional tillage – 1.37 vs. 0.76 hour ha^{-1} according to Rego (1998, cited by Sims and Kienzle, 2006) and thus reduces this handicap, making 2WTs potentially more attractive for users and owners/service providers.

Reduced or no tillage in combination with surface mulching and crop rotation and association, form the basis of conservation agriculture (CA) (Kassam et al., 2009). As stated above, CA may increase the viability of small-scale mechanization. The spread of appropriate mechanization may in turn increase the adoption of CA in SSA, which has so far been slow (Derpsch et al., 2010). Indeed, the lack of appropriate implements to seed at the right depth through an organic mulch and with minimum soil disturbance is recognized as one of the major constraints – albeit not the only one – faced by African smallholders on adopting CA (Hobbs et al., 2008; Giller et al., 2009; Johansen et al., 2012). Delivering mechanized CA to smallholders in SSA (e.g. via service providers) may stimulate CA adoption, a technology that has the potential to maintain the productive capacity of soils (Chivenge et al., 2006) and in certain circumstances to increase productivity by allowing early planting (Haggblade and Tembo, 2003) and by improving rainwater use efficiency (Rockström et al., 2009; Thierfelder and Wall, 2009). Another potential synergy between agricultural mechanization and CA may come from the reduced use of crop residues for animal fodder that would be expected from a shift from animal draught power to tractor power, resulting in an increased fraction of crop residue potentially available for surface mulching. For example, Baudron et al. (2014) estimated that substituting mechanization for animal draught power would increase the proportion of farmers in the Ethiopian Rift Valley retaining at least 1 t ha^{-1} of crop residues in their fields from 3% to 25%. Oxen represent a large proportion of the cattle owned by small-scale farmers in many parts of Eastern and Southern Africa (e.g. most of Ethiopia, central

Mozambique, Northern Tanzania, Table 3). Estimating the live weight of oxen in Eastern and Southern Africa at 250 kg and estimating their daily ingestion at 2% of their live weight, several tonnes of biomass are consumed every year by these animals (Table 3), although they may only provide a few weeks of work annually. Therefore, substituting 2WTs for oxen would release this biomass in many parts of SSA where animal traction is important, and this could be made available for surface mulch.

Tapping the above-synergies between small-scale mechanization and CA is made possible by the recent development of seeders and other implements from newly emergent industrial economies such as India, China and Brazil, which is the topic of the next section.

4. Conservation agriculture and other farm operations using a two-wheel tractor

4.1. Conservation agriculture using a two-wheel tractor

Several CA seeders for 2WTs are now commercially available, from countries like China, India and Brazil. Based on the technologies/principles used for seed placement, two broad categories of CA seeders can be distinguished: (1) rotary strip-tillage seeders, and (2) tow-behind or toolbar-based seeders.

Rotary strip-tillage seeders are based on a modification of conventional rotary cultivators, (Figure 5a). Seeders using this principle have low draft requirements, resulting in the possibility to use up to six openers with no need for extra weight to penetrate the ground (Justice, 2004; Baker, 2007). These seeders, however, tend to move a lot of soil, incorporate a large fraction of crop residues (no longer available as surface mulch), and cannot be used in rocky soils (Baker, 2007). At least two companies manufacture rotary strip-tillage seeders on a commercial basis, one in China (www.chinalyjx.com/en) and one in India (www.nationalagroinds.com). Several more rotary strip-tillage seeders are in the development stage (Jin et al., 2014).

Tow-behind seeders are generally adapted from draught animal seeders (Figure 5b), are usually one or two-row and use discs or tines and are manufactured on a commercial basis by two Brazilian companies (www.fitarelli.com.br, www.knapik.com.br), two Indian companies (www.khedutagro.com, www.nationalagroinds.com, the seeder from National Agro Industries can be mounted behind a rotary cultivator and used for rotary strip-tillage or can be towed alone for direct seeding), and one Kenyan company (www.ndumekenya.com). Others are in the development stage in Asia (Jin et al., 2014) and East Africa (Sims et al., 2012). Toolbar-based seeders use various discs or tines that can be mounted on the tool bars in different configurations: single-row, two-row, or multiple-row. At least one toolbar-based seeder – the ARC Gongli seed drill - is commercially available from China. Tow-behind and toolbar-based seeders minimize soil disturbance and maximize the fraction of crop residue retained as surface mulch. However, the small footprint and light weight of 2WTs translate into low tractive ability, limiting the number of tines that can be pulled in untilled conditions (to four or fewer tines in hard soils). Using discs rather than tines increases residue handling capacity, but also requires added weight for adequate soil penetration. However, the overall weight of the machine is limited by the fact that it needs to be lifted by the operator when turning.

Therefore, rotary strip-tillage seeders, tow-behind and toolbar-based seeders all present advantages and drawbacks. The choice of a particular seeder is thus sitespecific, and depends on factors such as soil type, soil moisture content at the time of seeding, amount of residues retained as surface mulch, etc. In addition to the soil engagement parts, the seed metering systems are equally crucial components of CA seeders. Fluted rollers are a common and inexpensive mechanism used for continuous seed metering for crops like rice, wheat, grain legumes and some oil seed crops. For row crops like maize, beans, and many vegetables, more expensive and more sophisticated seed meters are needed to singulate seeds. Brazilian CA seeders with singulating horizontal plates have been on the market for some time in SSA but their high costs have greatly limited their adoption. Recently inexpensive inclined and vertical plate singulating seed meters have come onto the market in India and China and have been incorporated into many existing 2WT CA seed drill designs.

Although the number of CA seeders commercially available is small, the number of models in prototype development stages exceeds 20, with more coming onto the development scene every year.

4.2. Transport, post-harvest operations, and irrigation

As mentioned above, the use of 2WTs for multiple purposes - including transport, post-harvest operations and water pumping – is a main factor explaining the profitability and spread of 2WTs in Bangladesh (and elsewhere in South and Southeast Asia). Simple equipment including trailers, threshers, and water pumps can be easily procured and even produced locally (Diao et al., 2012; Figure 5c and d). Moreover, these operations are not time-bound, nor synchronic, and are thus well suited for the development of the rental market (Binswanger, 1984; see section below on business models).

Transport, is often one of the first uses of new mobile power sources, once they are made available (Binswanger, 1984). Transport is a major force shaping farming systems, by connecting farming communities to other centers of demand (Binswanger and Pingali, 1988; Tiffen, 2003). As pointed by Godfray et al. (2010), poor transport may negatively affect agricultural productivity: (1) by raising the farm-gate cost of inputs (such as fertilizer), leading to low input use; (2) by raising the cost of moving commodities to the market, leading to farmers choosing not to improve agricultural productivity because of poor returns; and (3) by leading to high losses of commodities (particularly perishable ones) before they reach the market. The so-called 'first mile' - i.e. the distance from the farm to the collection point – often represents a small fraction of the total logistic chain (from the farm to the final market) but a high proportion of the total cost of transporting agricultural commodities from the farm to market in SSA. For example, the first mile only represents 0.4 to 10% of the logistic chain length, but 20 to 37%of the transport cost, for high value agricultural commodities (e.g. French beans, bananas, potatoes) in Kenya (KENDAT and IFRTD, 2013). The transport cost of the first mile can be reduced by using appropriate 'Intermediate Means of Transport' (IMT), which are defined as transport means with a carrying capacity below 1,000 kg used for short distances, typically below 20 km (i.e. they are intermediate between human portage and large-scale transport means; Starkey, 2000). Trailers pulled by 2WTs are part of the wide basket of IMTs (Figure 5c). The cost of transport per unit of volume and unit of distance varies with the demand level and the transport distance: although the transport cost with a 2WT may be higher than with an ox cart for a distance of 10 km (regardless of the annual demand for transport), it may be lower for a distance of 50 km with any annual demand for transport exceeding 30 tonnes (Starkey, 2002).

Once new sources of power become available, they are also commonly used for selected operations that are power-intensive and either (1) require little human control - which is typical of post-harvest operations such as shelling (Figure 5d), threshing and milling, or (2) are unprofitable when un-mechanized – which is typical of water pumping (Binswanger, 1984). Even at low labour wages, mechanizing these operations is often profitable (Binswanger, 1984). In addition, the combination of small-scale irrigation with small-scale mechanization could have synergistic effects. First, mechanization schemes in SSA have mainly been successful when coupled with irrigation (Mrema et al., 2008). Second, the collapse of large state-run irrigation schemes across Africa has brought a new paradigm centred on small-scale irrigation (Kay, 2001), creating opportunities for small pump sets powered by 2WTs to be used in small-scale irrigation. Third, the use of low horsepower engines for water pumping may precede (and stimulate) their use for other agricultural operations, as was the case in South and Southest Asia (Biggs, 2012).

5. Ensuring the viability of private sector business models

The collapse of virtually all the government-run tractor schemes - which were popular up to the 1990s in most of SSA - demonstrates the need for a new approach to mechanization that involves the private sector. It is commonly understood that through the development of market systems, replication, dissemination and uptake of new technologies are most likely to occur (Magistro et al., 2007). However, in many local situations, weaknesses in technology market systems can be found that inhibit the uptake of new and innovative agricultural technologies by smallholder farmers. In recent years the interdependence of the private sector and their client base has been highlighted through the concept of ‘creating shared value’ (Porter and Kramer, 2011) and efforts are being taken to understand how technologies and business models can be developed simultaneously to cater for the demand from the large consumer base of smallholder farmers (London and Hart, 2010).

The experience of International Development Enterprises (iDE) in Bangladesh has demonstrated the possibility of harnessing the power of the market to drive technology adoption among the rural poor, by involving the private sector in the development and promotion of agricultural technologies (Magistro et al., 2007). Similarly, a market oriented approach to business development may be used in SSA to foster the adoption of 2WTs and their ancillary equipment. This approach could be guided by the lessons learned from previous experiences in market development, which can be distilled into a set of six: (1) facilitating the emergence of private rural service providers; (2) considering the need for a broker; (3) linking mechanization and other input business models to output business models; (4) broadening the range of services offered; (5) bundling hiring services; and (6) providing kick-start subsidies for private sector investment in mechanization service provision. These principles will be elaborated below.

In SSA, smallholders are capital constrained and may not be in a position to purchase 2WTs individually. Alternative forms of service provision need to be examined with mechanization services provided either through independent service providers or through group ownership of mechanization assets (Landers, 2000, Sims et al., 2011, Wongtschowski et al., 2013). Service hiring is not new to SSA, as many farmers currently hire labour and/or draft power (Table 4). Service business models could be driven by private sector dealers and manufacturers linking up to service providers and operators at the local level. However, the private sector may be reluctant to invest in mechanization in areas where agricultural markets are weak, awareness and demand for machinery and their services are absent and farmers are vulnerable to shocks and stresses. Under these circumstances intermediaries – such as NGOs, government or donor supported projects – may be needed to facilitate linkages between the private sector and smallholder farmers and thus develop viable business models (Kahan, 2007; London and Hart, 2010). Once demand can be assured, intermediaries would be expected to 'exit', allowing the private sector to step in and scale-out the technologies. Increasing attention is being paid to identifying such 'scalability' from the outset when designing interventions in market systems (Cooley and Kohl, 2006). In contrast, where markets are stronger with better rewards for investment, the private sector is more likely to emerge as the initial and main driver of the chain omitting the need for intermediaries.

The existence of market-oriented farm enterprises – and their associated cash flow – is a prerequisite to afford either buying or renting farm machinery (Mrema et al., 2008). It is thus crucial to recognize the inter-linkage between input markets (including mechanization) and output markets (Lundy, 2012), with smallholders lying at the interface of the two. The viability of a mechanization service provision business also depends on mechanization use rates, which can be greatly extended by considering off-farm services such as transport and road construction and maintenance (Petts, 2012). This allows 2WTs to be in productive use for a greater part of the year and to reduce the unit cost of custom work. The cost of a unit (service of product) may also be reduced through 'bundling' mechanization services with complementary packages of inputs and materials, assistance in marketing produce, financial services and general advisory service support. A form of bundling which is likely to appeal to customers is the integrated provision services through support centres that offer a range of goods and services as a 'one-stop-shop' where constraints can be addressed in an orchestrated manner (Downing, 2001; Sims et al., 2011). In areas where markets are weak, and where smallholders face difficulties in paying for knowledge-based support services (e.g. information, training, advisory services), these services may be 'embedded' in a commercial transaction in order for them to be affordable to smallholders (Tanburn, 2002; Hitchins et al., 2005; Kahan, 2007, 2011).

In weak and distorted markets where the private sector is reluctant to invest, public sector support may be needed to 'kick-start' development. Subsidies may create awareness of the new technologies and develop the market, but a time limit would need to be set for phasing them out (Tanburn, 2002; Gibson, 2001; Downing, 2001; Meyer-Stammer, 2006; Kahan, 2007; DFID and SDC, 2008). The challenge is how best to design 'smart' subsidies in a way that develops rather than distorts the market for mechanization services.

6. Likely social and environmental impact

6.1. Mechanization without consolidation and labour displacement

Large-scale mechanization (based on 4WTs) generally favours large-scale farmers who have access to capital, as illustrated by the Indian mechanization model (see Section 3.1. above). This inequitable access to mechanization may widen the gap in productivity and efficiency between large farms and small farms, and fuel land consolidation – where larger farms gradually absorb adjacent smaller farms ─ a consequence of mechanization programmes (based on 4WTs) often witnessed (Mrema et al, 2008). In the process, smallholders and hired labour are often displaced (Binswanger et al., 1995; Brown et al., 2004). Although some authors (e.g.

Mrema et al., 2008) have argued that land consolidation – to optimize the field efficiency of 4WTs and their ancillary equipment – may be more desirable than adapting mechanization to the needs of small farms, we argue here for the opposite. African agriculture is dominated by small farms, with 2/3 of all farms smaller than 2 ha (Altieri, 2009). These small farms sustain the livelihood of millions and are the backbone of local food systems (Rosset, 2008). In addition to their direct contribution to food security, the productivity, per unit area, of small farms is often higher than that of larger farms, a phenomenon known as the 'inverse farm size – productivity relationship' (Heltberg, 1998).

The capital needed for the purchase, operation and maintenance a 2WT is much lower than for a 4WT (Diao et al., 2012). As a result, mechanization models based on 2WTs tends to promote equitable access to mechanization, as illustrated by the Bangladesh model, where all farmers, even the poorest, have access to mechanization services (Alam, 2003). In addition, a 2WT can get into and operate efficiently in much smaller fields than a 'conventional 4WT' (i.e. excluding mini-tractors of 25 hp or less, these being of similar size than 2WTs, but more expensive and more sophisticated). In fields that are smaller than 1000 m^2, 2WTs have a higher field efficiency than 'conventional 4WTs', which can spend more than half their time simply lifting the implement, turning and positioning for the next run in fields of this size.

In addition, the mechanization model proposed here – where farmers access mechanical services through service providers (see Section 5) – is unlikely to result in labour displacement. Only the most power-intensive operations (e.g. primary soil tillage, post-harvest operations) are likely to be mechanized. Other operations – which are unlikely to be mechanized until labour wages increase (e.g. weeding, harvesting) - will continue to be performed through (family and hired) labour. Therefore, 2WTs are likely to be a complement, not a substitute, for human labour.

6.2. Mechanization without soil degradation and biodiversity loss

A 2WT is lighter in weight than a 4WT and so exerts less ground pressure and results in less soil compaction. In addition, the use of 2WTs in rainfed condition implies that they are used for minimum tillage (see Section 3.2) as they are not powerful enough to plough in such conditions (Holtkamp and Lorenz, 1990; Singh, 2006). Therefore, the use of 2WTs can be considered a form of mechanization that potentially reduces soil degradation, a negative effect of mechanization often witnessed in the tropics (Lal, 1985) and elsewhere.

A shift from animal draught power to tractor power could result in more crop residue being retained in the field (Section 3.2), rather than used as feed. This would result in an increased input of carbon to the soil, leading to maintained or improved soil fertility. Indeed, crop residues represent the main organic input available to SSA farmers (Lal, 2005). Animal manure may be an important source of carbon in some farming systems, but its application to fields distant from the homestead is generally limited (Zingore et al., 2007; Figure 4b).

Maintaining landscape heterogeneity is key to conserving agricultural biodiversity (Fischer et al., 2006). Land consolidation leads to a loss of spatial heterogeneity (e.g. hedgerows) and temporal heterogeneity (as a large area is under the same management regime at any given time) (Benton et al., 2003). Therefore, by allowing the maintenance of a mosaic of small fragmented fields, 2WT-based mechanization may be favourable to biodiversity. In addition, the 2WT's narrower track (1.1 meter wheel base i.e. far narrower than the track of a ‘conventional 4WT’) means it can operate in fields where scattered trees – key ecological structures for agricultural biodiversity and a number of ecosystem services (Manning et al., 2006) - are retained.

7. Conclusions: why would appropriate mechanization work this time?

Past initiatives of promoting mechanization in SSA have generally failed (Mrema et al., 2008). The lack of demand for mechanization and the lack of supporting infrastructure were major reasons for this failure. As agriculture in SSA has become more intensive and more commercially oriented, we are confident that this demand has increased. Moreover, the boom in ownership of motorcycles and auto-rickshaws in many SSA countries has been accompanied by the development of repair services and increased availability of fuel and lubricants that could benefit 2WT market systems. The approach used by the past initiatives may have also been inappropriate, with a focus on large machines not suitable for small and fragmented fields, and/or too costly for many African smallholders and private sector hire-service providers, and a reliance on the public sector that led to inefficient and uneconomic government-run tractor hire schemes. Appropriate and equitable mechanization may be achieved by using 2WTs – which are not powerful enough to plough in the rainfed conditions but suited to CA – and involving the private sector through business model development.

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Table 1 – Mean age of rural household’s head in 14 areas targeted by the ACIAR-funded SIMLESA project in Eastern and Southern Africa (source: SIMLESA, 2014)

Country	**Area**	**Age of rural household heads**
Ethiopia	Pawe	42.8 ± 13.6
	Bako	40.1 ± 13.1
	Adami	41.9 ± 13.4
	Hawassa	41.0 ± 12.8
Kenya	Western	48.4 ± 15.2
	Eastern	48.1 ± 14.5
Malawi	Lilongwe-Ntcheu	40.2 ± 13.7
	Kasungu-Mchinji-Salima	40.3 ± 15.2
	Balaka	44.1 ± 16.6
Mozambique	Manica	48.0 ± 15.5
	Tete	44.4 ± 15.3
	Sofala	44.5 ± 14.6
Tanzania	Northern	45.9 ± 14.2
	Eastern	44.6 ± 13.6

Table 2 – Prevalence of HIV/AIDS and proportion of female-headed households in six countries of Eastern and Southern Africa (source: World Bank, 2011).

Country	Prevalence of HIV/AIDS (% of population ages 15-49)	Proportion of female-headed households (%)
Ethiopia	-	22.8 (a)
Kenya	6.3	31.7 (b)
Malawi	11	24.7 (c)
Mozambique	11.5	26.4 (b)
Tanzania	5.6	24.5 (a)
Zimbabwe	14.3	37.7 (d)

(a) data from 2005; (b) data from 2003; (c) data from 2004; and (d) data from 2006.

Table 3 – Mean proportion of oxen in the cattle herd of 14 areas targeted by the ACIAR-funded SIMLESA project in Eastern and Southern Africa, and estimated quantity of biomass consumed annually by oxen in each farm, estimating the live weigh of one ox at 250 kg and its daily intake at 2% of its live weight (source: SIMLESA, 2014; TLU: Tropical Livestock Unit)

Country	**Area**	**Proportion of oxen in the herd (% TLU)**	**Estimated quantity of biomass consumed by oxen (t year^{-1} farm^{-1})**
Ethiopia	Pawe	51.1 ± 30.8 %	2831 ± 2570
	Bako	38.2 ± 22.2 %	3541 ± 2909
	Adami	34.2 ± 21.2 %	4182 ± 4314
	Hawassa	31.2 ± 25.7 %	2424 ± 3013
Kenya	Western	10.3 ± 24.7 %	584 ± 1770
	Eastern	0.2 ± 2.9 %	13 ± 227
Malawi	Lilongwe-Ntcheu	1.3 ± 10.0 %	69 ± 798
	Kasungu-Mchinji-Salima	0.0 ± 0.0 %	0 ± 0
	Balaka	0.0 ± 0.0 %	0 ± 0
Mozambique	Manica	22.4 ± 27.3 %	2428 ± 5890
	Tete	3.3 ± 11.7 %	237 ± 1176
	Sofala	0.0 ± 0.0 %	0 ± 0
Tanzania	Northern	14.5 ± 24.4 %	1962 ± 4077
	Eastern	6.9 ± 20.6 %	261 ± 1486

Table 4 – Proportion of rural households hiring labour, hiring oxen and owning a motorbike in 14 areas targeted by the ACIAR-funded SIMLESA project in Eastern and Southern Africa, (source: SIMLESA, 2014)

Country	Area	Proportion of households hiring labour (%)	Proportion of households hiring oxen (%)	Proportion of households owning a motorbike (%)
Ethiopia	Pawe	53%	8%	0%
	Bako	26%	13%	0%
	Adami	51%	14%	1%
	Hawassa	40%	7%	1%
Kenya	Western	56%	51%	6%
	Eastern	74%	12%	5%
Malawi	Lilongwe-Ntcheu	8%	10%	1%
	Kasungu-Mchinji-Salima	21%	19%	1%
	Balaka	11%	3%	0%
Mozambique	Manica	35%	28%	7%
	Tete	43%	20%	8%
	Sofala	41%	0%	1%
Tanzania	Northern	48%	51%	3%
	Eastern	51%	22%	3%

Figure legends

Figure 1 – (a) population trend in six countries of Eastern and Southern Africa from 1960 to 2010 (source: World Bank, 2011); (b) trend in the number of undernourished people in sub-Saharan Africa from 1992 to 2007 (source: FAO, 2009); (c) trend in the number of urban persons per active person in agriculture in six countries of Eastern and Southern Africa from 1980 to 2010 (calculated from World Bank, 2011); and (d) trend in the value added by agriculture in six countries of Eastern and Southern Africa from 1980 to 2010 (source: World Bank, 2010)

Figure 2 – Comparison of (a) the density of tractors, (b) the density of cattle and buffaloes – proxy for the availability of draught power, and (c) the density of economically active people in agriculture in six countries of Eastern and Southern Africa, compared to India (calculated from FAOSTAT, 2012)

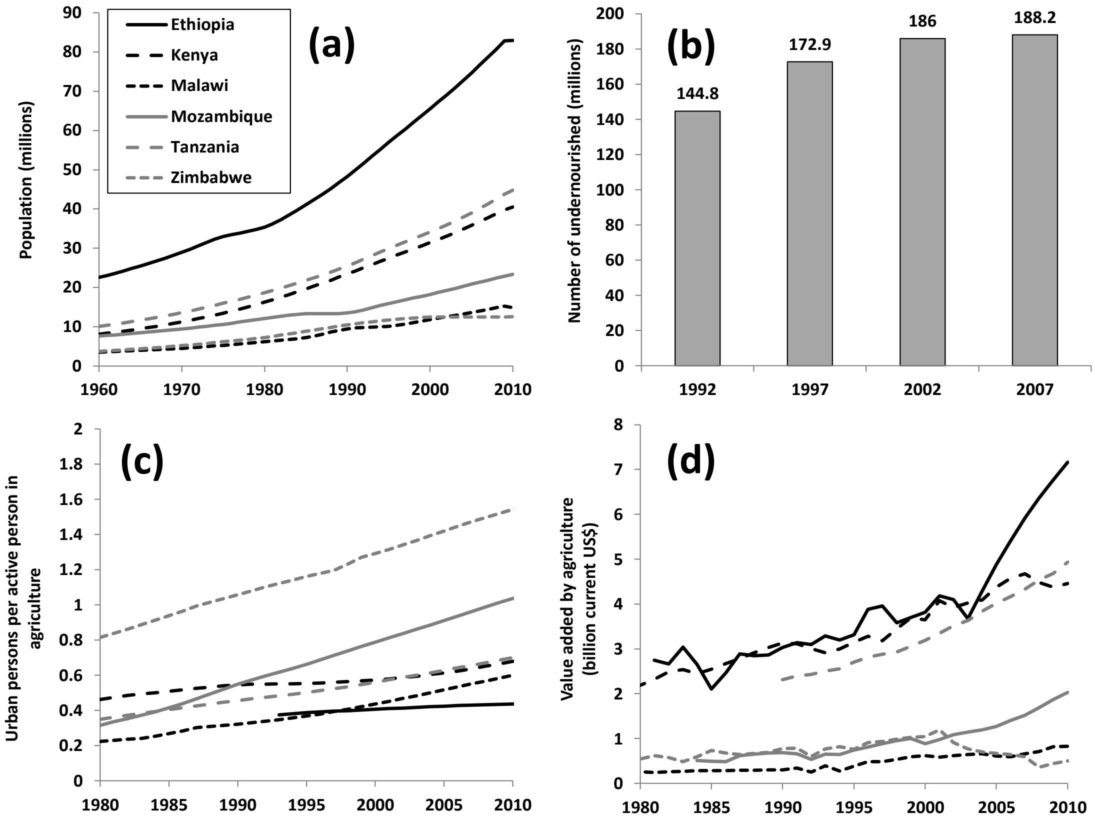
Figure 3 – Income structure of farming households of different wealth categories in Northern Zimbabwe (source: Baudron, 2011).

Figure 4 - – Mean cereal production per farm in the Central Rift Valley of Ethiopia as a function of the number of pairs of oxen (source: Baudron et al., 2014); (b) annual N input from manure to plots as a function of their distance to the homestead and for different wealth categories in North-East Zimbabwe (source: Zingore et al., 2007); (c) cotton yield as a function of the planting date in Northern Zimbabwe (the dotted line represent the attainable yield, source: Baudron, 2011); and (d) mean monthly

allocation of labour for different farm types in Northern Zimbabwe (source: Baudron et al., 2012b).

Figure 5 – (a) Strip-tillage using a modified Chinese seed drill from Danyang Liangyou Machinery Co. Ltd. (www.chinalyjx.com/), (b) direct seeding using a Brazilian seeder from Fitarelli Máquinas Agrícolas (www.fitarelli.com.br), (c) two-wheel tractor being used for transport in Northern Tanzania, and (d) two-wheel tractor shelling maize using a locally-manufactured sheller, in Northern Tanzania

Figure 1



(a)
Population (millions)
Ethiopia
Kenya
Malawi
Mozambique
Tanzania
Zimbabwe
90
80
70
60
50
40
30
20
10
0
1960
1970
1980
1990
2000
2010
(b)
Number of undernourished (millions)
144.8
172.9
186
188.2
200
180
160
140
120
100
80
60
40
20
0
1992
1997
2002
2007
(c)
Urban persons per active person in agriculture
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1980
1985
1990
1995
2000
2005
2010
(d)
Value added by agriculture (billion current US$)
8
7
6
5
4
3
2
1
0
1980
1985
1990
1995
2000
2005
2010

Figure 2

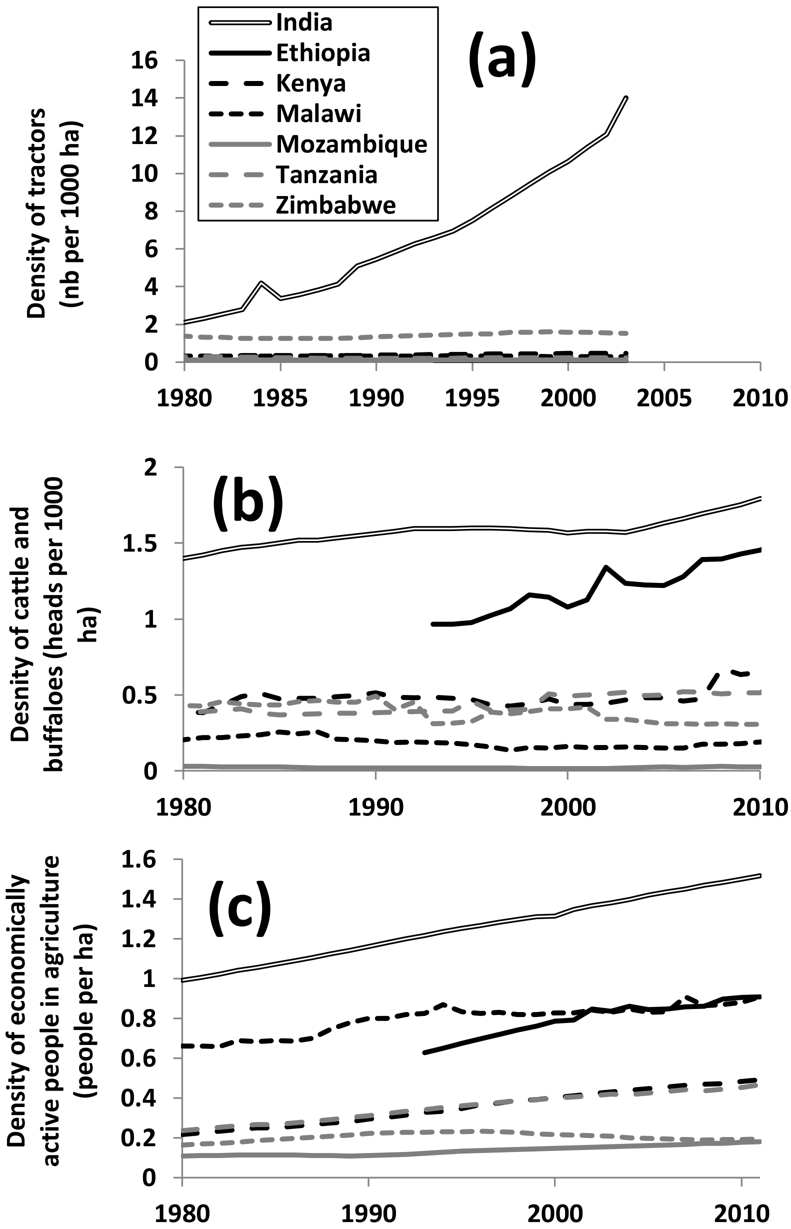

(a)
India
Ethiopia
Kenya
Malawi
Mozambique
Tanzania
Zimbabwe
Density of tractors (nb per 1000 ha)
16
14
12
10
8
6
4
2
0
1980
1985
1990
1995
2000
2005
2010
(b)
Desnity of cattle and buffaloes (heads per 1000 ha)
2
1.5
1
0.5
0
1980
1990
2000
2010
(c)
Density of economically active people in agriculture (people per ha)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1980
1990
2000
2010

Figure 3

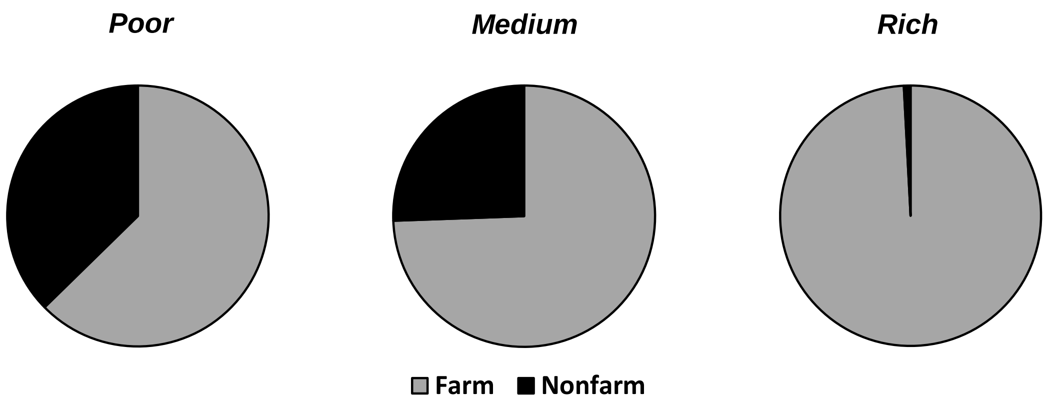
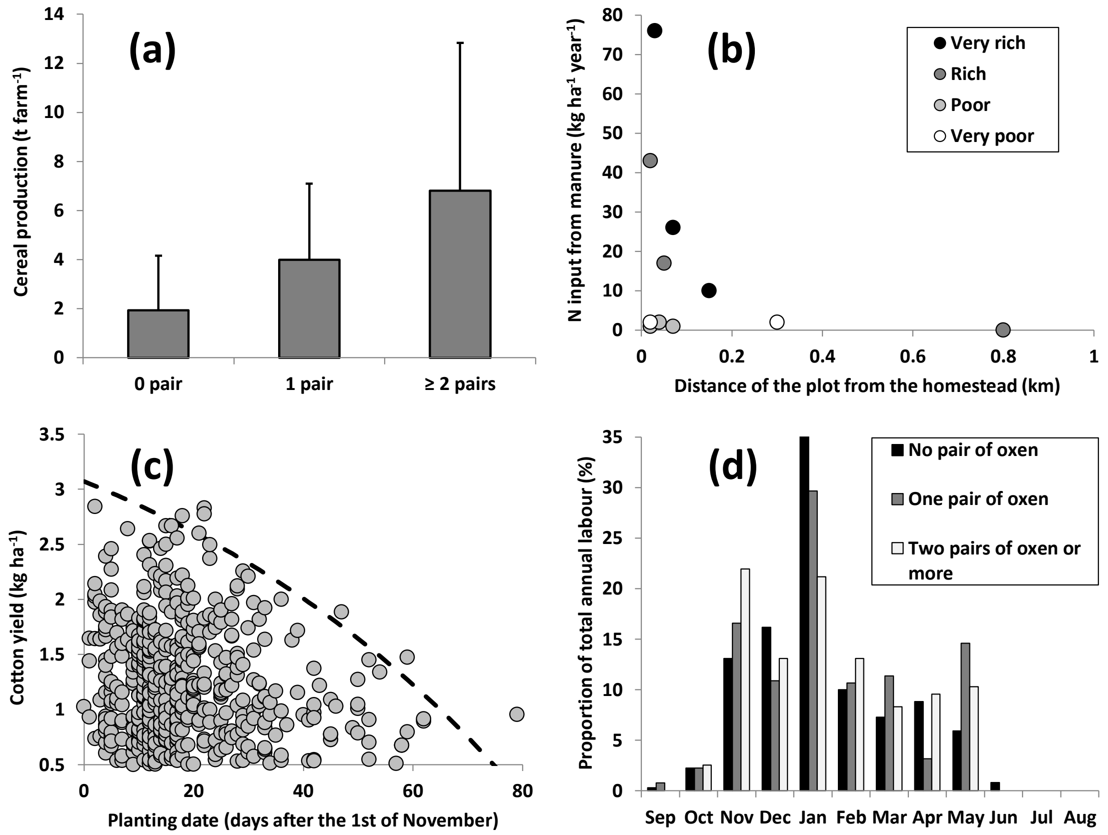


Figure 4



(a)
Cereal production (t farm-1)
0 pair
1 pair
≥ 2 pairs
(b)
N input from manure (kg ha-1 year-1)
Distance of the plot from the homestead (km)
Very rich
Rich
Poor
Very poor
(c)
Cotton yield (kg ha-1)
Planting date (days after the 1st of November)
(d)
Proportion of total annual labour (%)
No pair of oxen
One pair of oxen
Two pairs of oxen or more
Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug

Figure 5