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ORIGINAL PAPER

The forgotten agriculture-nutrition link: farm technologies and human energy requirements

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Abstract

In the quest to reduce global under- and malnutrition, which are particularly high among smallholder farmers, agriculture-nutrition linkages are receiving increasing attention. Researchers have analyzed the link between the quantity and diversity of food that farmers produce and nutritional outcomes but paid limited attention to a third agriculture-nutrition link: the link between *how* food is produced and nutritional outcomes. This neglect persists despite the majority of smallholder farmers relying on hand tools for farming, which implies heavy physical work and, thus, high energy requirements. To address this research gap, this study compares the energy requirements of farm households in rural Zambia that are characterized by three different levels of mechanization: hand tools, animal drought power, and tractors. 1638 days of detailed time-use and nutrition data were collected from 186 male and female adults and boys and girls during different seasons (land preparation, weeding, and harvesting/processing) using an innovative picture-based smartphone app called "Timetracker". This data served to calculate different proxies for physical activity and energy requirements using "Ainsworth's Compendium of Physical Activities". The results suggest that detailed time-use data offers great potentials to study physical activity and energy requirements. The findings show strong linkages between farm technologies, physical activity levels, and energy requirements, suggesting that this agriculture-nutrition link deserves more scientific and political attention to reduce under- and malnutrition among smallholder farmers.

Keywords Food systems · Time-use · Africa · Nutrition-sensitive agriculture · Agricultural mechanization · Caloric requirements

1 Introduction

Across the world, 690 million people do not have access to enough calories and are undernourished (FAO et al., 2019). Two billion people lack access to enough micronutrients and are malnourished, a phenomenon called hidden hunger (IFPRI, 2016). Since under- and malnutrition are particularly widespread among smallholder farmers (FAO et al., 2019; IFPRI, 2016), agriculture-nutrition linkages—or nutrition-sensitive agriculture—have received much attention (Dangour et al., 2013; Griffin, 2010; Turner et al., 2013). Such linkages are well recognized from a food quantity perspective—a high farm production raises the availability of food and thus reduces undernutrition—and a food quality perspective—linking farm and consumption diversity (Sibhatu & Qaim, 2018).

One agriculture-nutrition linkage has been forgotten, however.[1] This is the link between *how* farmers produce food and their nutritional status. This link is neglected despite the majority of smallholder farmers, especially in Africa, relying on hand tools for farming (Daum & Birner, 2020), which implies heavy physical work and high energy requirements, in particular during the hunger season when the previous

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[1] The term *forgotten* rather than *neglected* is used since this link has received more attention previously. In Germany, for example, the Kaiser-Wilhelm-Institut (KWI) für Arbeitsphysiologie (*occupational physiology*; founded 1913) studied the link between farm technology, caloric requirements and labour productivity, partially motivated by war efforts (Heim, 2003). In 1948, the KWI became the Max-Planck-Institut (MPI) für Arbeitsphysiologie. In 1956, one of its departments became the MPI für Ernährungsphysiologie (*nutrition physiology*), which, for example, studied the link between farm technology and drudgery and provided assistance for an FAO report on nutrition and work efficiency (FAO, 1957).

year's harvest is dwindling (Sitko, 2006). In contrast, members of farm families relying on non-human energy may have significantly lower caloric requirements. If people are undernourished, a reduction in caloric requirements could reduce undernutrition, which may in particular benefit household members who are most vulnerable to undernutrition such as women and children. However, if diets are not deficient in energy, modern farm technologies may contribute to obesity. Human energy replacing farm technologies include agricultural mechanization, which has received renewed interest in Africa (Adu-Baffour et al., 2019; Daum & Birner, 2017, 2020) and grown rapidly in Asia (Takeshima, 2017; Wang et al., 2016) as well as herbicides, which are gaining momentum across the developing world (Haggblade et al., 2017).

Several studies suggest a linkage between physical activity during farming and nutritional outcomes. In India, farming households, women, in particular, are thinner than households pursuing other activities (Barker et al., 2006; Headey et al., 2012). In Tanzania and India, farmers' weights fluctuate with the agricultural season (Kinabo et al., 2003; Rao et al., 2009). In Ghana, time allocated to agriculture is a key determinant of the nutrition status of females (Higgins & Alderman, 1997). However, none of these studies pays specific attention to the actual farming technologies used. An exception is Komatsu et al. (2019) who found in Tanzania that the BMI of women in households using knapsack sprayers is correlated with the time spent in weeding. In the same study, the authors lament a general lack of data for studying linkages between farm technologies, labor, and nutrition.

Studying such linkages may be complex because of several reasons as the following aspects related to mechanization show. 1) There can be a *seasonal effect*: Mechanizing one farming step may have implications on subsequent farming steps. For example, if only land preparation is mechanized, which is common during early mechanization (Binswanger, 1986), farmers may cultivate more land, thereby increasing the workload for weeding and harvesting (Daum & Birner, 2020). Mechanized land preparation may, however, also reduce weed growth (Baudron et al., 2019), which would reduce the time and energy requirements for weeding. 2) There can be a *substitution effect*: Time saved due to mechanization can be shifted to alternative activities, which may require more or less energy than the energy saved by mechanization. 3) There can be a *gender effect*: Different household members may be affected differently, depending on the division of labor (Blackden & Wodon, 2006; Doss, 2001; Farnworth et al., 2016). 4) Lastly, there are differences between mechanization by animal draught power and tractors. Both may be associated with different energy requirements. Moreover, while animals require labor-intensive activities, such as feeding, throughout the year, they may be usable for a wider range of labor-saving (and, thus, energy-saving) activities compared to tractors.

Collecting data, which can reflect this complexity, is a major challenge. To capture the seasonal effect, data from different farming steps are required. To capture the substitution effect, it is essential to cover all types of farm and non-farm activities. To assess the gender effect, it is essential to

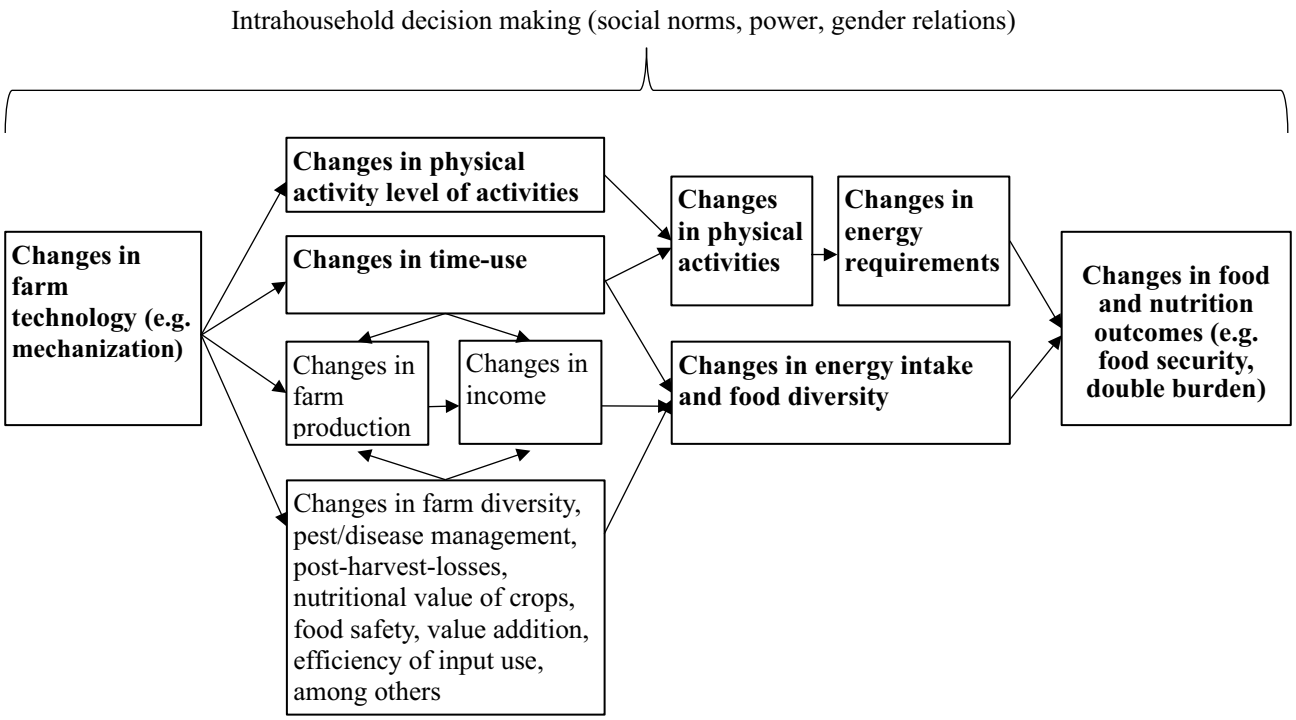

Fig. 1 Conceptual framework

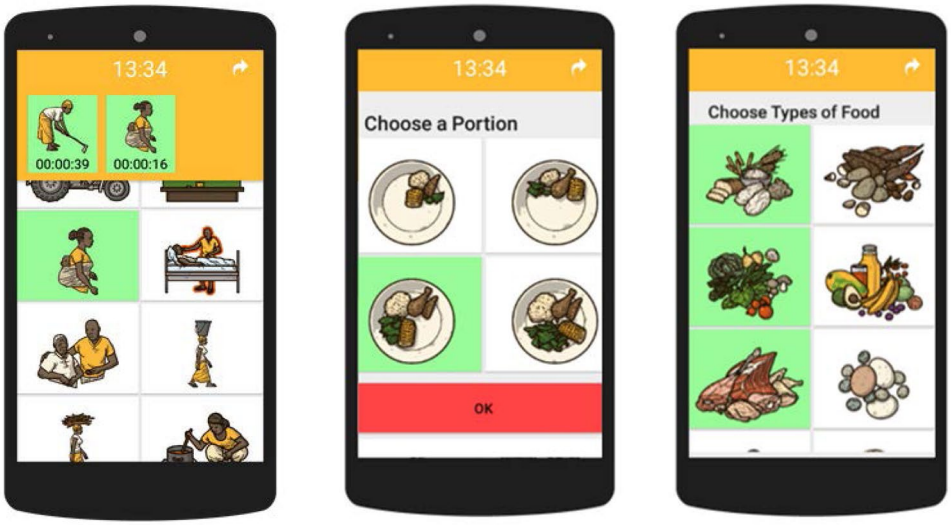

Fig. 2 Interfaces of the Time-tracker

collect data from different household members, including children, which are often neglected, even though 60% of all child labor takes place in agriculture (ILO, 2019).

To our knowledge, the complex linkage between farm technologies, energy requirements, and nutritional outcomes has thus not been studied so far. The present study aims to contribute to addressing this knowledge gap, focusing on agricultural mechanization. The study has two major objectives: 1) to establish a proof-of-concept for a data collection method that adequately captures the above-mentioned complexities, which is based on the collection of detailed self-recorded time-use data and subsequent conversion of this data into energy requirements; 2) to assess the relevance of this forgotten agriculture-nutrition linkage by comparing the differences in energy requirements of smallholder farming households in Zambia, applying three different levels of mechanization. Considering that cross-sectional data was used, this paper should be understood as a proof-of-concept case study. Establishing causality would require panel data or, preferably, a randomized control trial. However, given the complexity of the linkage pointed out above, it appears useful to conduct an explorative study such as this one before conducting a large-scale randomized controlled trial.

2 Materials and methods

2.1 Conceptual considerations

Figure 1 displays how changes in farm technologies can be linked with nutritional outcomes. This paper focuses on changes in physical activity and time-use, which can affect nutritional outcomes by affecting caloric energy requirements. The linkages analyzed are in bold in Fig. 1.

Besides, there are other potential linkages. A well-established one is the production pathway: if new farm technologies allow households to produce more (through land expansion, higher yields, or lower post-harvest losses), they can consume or sell more, which may result in more and better food consumed. This link was important during the Green Revolution (Evenson & Gollin, 2003). Similarly, farm technologies that allow value addition may enhance food and nutrition outcomes (Malabo Montpellier Panel, 2018). Farm technologies can also affect food safety and quality, for example, applying pesticides more precisely can reduce food contamination (Carvalho, 2006) and better processing, storage, and transportation technologies can preserve food (and nutrients) and reduce contamination with fungus such as aflatoxins (Malabo Montpellier Panel, 2018). Guaranteeing food safety may give farmers access to markets paying higher prices (Malabo Montpellier Panel, 2018). Relatedly, farm technologies may affect the nutritional value of crops (Hornick, 1992) Farm technologies can also affect farm diversity. For example, farmers may focus on easy to mechanize crops such as maize (Kansanga et al., 2018). This can influence diets if farmers do not counterbalance reduced farm diversity by buying food from markets (Sibhatu & Qaim, 2018). Lastly, there is a time-use pathway. For example, farm technologies can influence the time available for cooking, which can influence household nutrition (Johnston et al., 2018), or the time available for pursuing other income opportunities, which allows the purchase of food.[2] Next to the identified linkages, there may be other linkages such as changing input use efficiency and pest/diseases management that can directly or indirectly affect food and nutrition outcomes, among others. All links can influence each other and there may be feedback loops. Moreover, the type

[2] There may also be other pathways, for example, an employment pathway: if mechanization leads to fewer employment opportunities for labourers, this can affect the nutrition in their households.

Table 1 Selected sample characteristics

Variable	Manual (I)	Animal (II)	Tractor (III)	Intergroup Comparison		
				I vs II	*I vs III*	*II vs III*
Land cultivated (ha)	2.3 (1.1)	4.8 (3.9)	8.4 (5.9)		***	**
Crop diversity	3.1 (1.1)	3.7 (1.1)	3.5 (1.0)			
Tropical livestock unit[1]	0.8 (1.0)	7.4 (7.9)	6.4 (8.0)	***	**	
Maize yield (tons/ha)	1.91 (1.6)	2.63 (1.6)	3.55 (1.9)		***	
Household size	6.6 (1.6)	7.8 (2.3)	6.7 (2.1)			
Hired labor (hours per ha cultivated)						
Land preparation	4 (12)	7 (25)	4 (10)			
Weeding	5 (24)	14 (49)	21 (47)			
Harvesting	9 (39)	8 (25)	17 (35)			
Frequency of animal draught weeding	0.32 (0.4)	0.69 (0.5)	0.51 (0.4)	**		
Pesticides (litres per ha cultivated)	1.5 (4.6)	8.8 (14.8)	5.4 (11.5)			

Standard deviation in brackets. Differences between means are based on Tukey tests and are indicated with *, **, and ***, which denote the significant differences at the 10%, 5%, and 1% level. [1]Tropical Livestock Unit with the following weights: cattle = 0.7, sheep = 0.1, goats = 0.1, pigs = 0.2, chicken = 0.01

of farm technologies adopted and the overall food and nutrition outcomes – as well as all intermediate linkages—are affected by social and cultural factors such as women's empowerment and gender roles.

2.2 Collection method for time-use and nutrition data

Collecting reliable data on time-use and physical activities in developing countries is challenging. Direct observations suffer from observer bias and are not feasible for longer periods and larger samples (Blackden & Wodon, 2006; Daum et al., 2019). Questionnaires are affected by recall bias (Arthi et al., 2018). Moreover, survey modules on time-use frequently group various physical activities (such as shelling, milling, winnowing, and grinding into processing), which makes the conversion to energy requirements difficult. Time-use diaries reduce recall bias but are not feasible when respondents are not literate and diaries are often based on coarse time slots – ranging from 15 to 30 min (Daum et al., 2019). Accelerometers are in principle a good way to study physical activity and energy expenditures (Limb et al., 2019; Zanello et al., 2017). However, such tools do not capture the type of activity done, for example, if an activity is agriculture-related, and have to be carefully calibrated to rural settings in developing countries before they should be used (Prista et al., 2009).

To address these challenges, data was collected using a novel approach: a picture-based smartphone application called Timetracker (Daum et al., 2018, 2019). The app allows participants to record time-use in real-time, which eliminates recall bias and uses only visual tools to ensure that persons with low literacy and children can record data. To record data, participants click on a picture of the respective activity when starting and click again when ending (see Fig. 2). Thus, the app facilitates the continuous tracking of *all* activities that individuals carry out during the day. Daum et al. (2019) have shown that the Timetracker improves data quality as compared to recall-based data collection.

The Timtracker comprises of 88 activities (see appendix 1). Participants can record up to three simultaneous activities, but this paper focuses on primary activities because respondents typically listed second and third activities that have no energy demands (e.g., listening to the radio) or low energy demands (e.g., chatting). When respondents consume food, a window pops up asking for the perceived quantity of food consumed by showing four differently filled plates and another window pops up where twelve different food groups are shown (see Fig. 2), which makes it possible to calculate food diversity scores.

2.3 Sampling

Data was collected in Eastern Zambia. Smallholder farmers, cultivating on average 2.3 ha of land, typically, maize, cotton, sunflowers, groundnuts, and tobacco (IAPRI, 2016), dominate the Eastern Province. Households rely mostly on manual labor and draught animals, but some use tractors for land preparation (IAPRI, 2016). The 2019 Global Hunger Index ranks Zambia 113th of the 117 assessed countries and reports its status as alarming.[3] At the national level, 41–46% of all households experience undernourishment. In the Eastern Province, most indicators are worse than the national average (Mukuka & Mofu, 2016).

To select the households, a two-stage-random-sampling approach was used based on the nationally representative Zambian Rural Agricultural Livelihood Survey (RALS) of 2014/2015. Four survey clusters that are geographical areas

[3] https://www.globalhungerindex.org/zambia.html

Table 2 Frequency of data days by type of household and season

Period	*Manual*				*Animal*				*Tractor*				Total
	M	F	B	G	M	F	B	G	M	F	B	G	
Land preparation	60	60	36	24	60	60	27	33	66	66	33	33	**558**
Weeding	60	60	33	18	60	60	27	30	66	66	30	33	**543**
Harvesting/processing	57	60	36	24	60	60	27	33	60	60	27	33	**537**
Total	**177**	**180**	**105**	**66**	**180**	**180**	**81**	**96**	**192**	**192**	**90**	**99**	**1638**

comprising of neighboring communities were randomly selected if at least five households were non-mechanized, five used animal draught power (ADP) and five used their own or hired tractors during land preparation. The households will henceforth be abbreviated as "manual-, animal- and tractor-households." Five to six households from each of these groups were randomly selected in each cluster. To be able to assess gender and age aspects, only households with at least one adult male, one adult female, and one child were selected. In total, 186 individuals from 20 manual-, 20 animal- and 22 tractor-households recorded data through the farming season. Table 1 shows selected sample characteristics of the three different groups.

In each household, the male household head, spouse, and one child (alternating between boy and girls) received a smartphone with the app and recorded data continuously for three days at five points during the 2016/2017 farming season. Daily random checks and validation with 24-h recall questions suggest a high data quality (Daum et al., 2019). In this paper, the focus is on land preparation, weeding, and harvesting/processing, which are considered the most labor-intensive farming steps (Binswanger, 1986). Table 2 provides an overview of the data days collected.

2.4 Conversion of time-use data to energy requirements

The time-use data was converted to physical activity levels and caloric energy requirements using the metabolic equivalent tasks (MET) of "Ainsworth's Compendium of Physical Activities", which compiles the energy demand of 600 different activities (Ainsworth et al., 2011). Such an approach has been pioneered by Tudor-Locke et al. (2009) who translated the activities of US-Americans into energy requirements and Deyaert et al. (2017) who calculated the energy requirements of different occupations in Belgium. The energy requirements calculated by such an approach closely resemble the energy requirements measured with accelerometers (Limb et al., 2019; van der Ploeg et al., 2010).

If the METs for specific tasks were unavailable, physical activity ratios (PAR) estimated by FAO et al. (2004) were used. We primarily rely on Ainsworth since their compendium is more comprehensive. Subsequently, both will be referred to as physical activity ratios and abbreviated as PAR, as both concepts essentially have the same meaning and physical activity ratios are the more tangible expression. The full table of MET/PARs for the different daily activities can be found in the appendix. Table 3 illustrates our conversion approach. A PAR of 2 means that twice as much energy is required for this activity as for sleeping with a PAR of 1.

2.5 Empirical methods

The paper focuses on four different proxies for physical activity and caloric energy requirements and one proxy for energy intake (see Table 4). Multiple regression analyses were performed with these proxies as outcome variables, according to the following specification:

Table 3 Illustrative Overview of the Conversion of Time-use to Daily Energy Requirements

Activity	Hours	PAR	Ainsworth Code	Hours x PAR	Daily PAR	Daily energy requirements for a stylized person
Sleeping	8	1.0	07,030 ("sleeping")	7.6	60.3/24 = **2.5**	BMR x Average PAR = 1559 × 2.5 = **3898**
Hoeing	6	5.0	08,241 ("…hoeing, moderate-vigorous")	30		
Chatting	4	1.3	07,060 ("… talking …")	5.2		
Walking	4	3,5	17,190 ("walking, …moderate)	14		
Hygiene	1	2.0	13,050 ("showering, toweling off…")	2		
Eating	1	1.5	13,030 ("eating, sitting")	1.5		
Total	**24**			**60.3**		

[a]The daily energy requirements are only shown for illustrative purposes. In this case, for BMR we assume a height of 170 cm, a weight of 65 kg, and an age of 35 years for males (see appendix 2)

Table 4 Variable descriptions

Variables name	Variables description
Outcome variables	
Daily physical activity ratio (Daily PAR)	Average PAR of all activities during the day weighted by the lengths of each of the activities across three days
Farm share time	Share of the time spend on farming activities across three days
Physical activity ratios related to farming (Farm PAR)	Average PAR of all farming activities during the day weighted by the lengths of each of the activities across three days
Farm share energy	Share of non-basal metabolic energy requirements caused by farming. Determined by the time spent farming and the physical activity ratios related to farming across three days
Daily portion size	Average daily portions sizes across three days. Portion sizes were indicated with differently filled plates: showing 25%, 50%, 75%, or 100% of the plate filled (see Fig. 2). These were counted as portions of 0.25, 0.5, 0.75, and 1 and accumulated for all meals during the day
Explanatory variables	
Mechanization	Power source for land preparation (manual labor, animal draught power, or tractor)
Gender	Gender of household member (head, spouse, boy, girl)
Community	The community of the household
Land size cultivated	Land size cultivated in hectares
Crop diversity	Number of field crops grown
Tropical livestock units	TLU using the following weights: cattle = 0.7, sheep = 0.1, goats = 0.1, pigs = 0.2, chicken = 0.01
Maize yields	Tons of maize harvested per hectare cultivated
Household size	*Number of household members*
Hired labor	Hired labor in hours per hectare cultivated for the respective season
Pesticide use	Liters per hectare cultivated
ADP weeding	Frequency of the use of animal draught power for weeding

$$Y_h = \alpha + ssM_h + \lambda \mathrm{X}_h + ss_2\left(M_h * G_h\right) + \gamma D + \varepsilon_h$$

Y includes outcome variables, M indicates the mechanization level, X is a vector of household characteristics, ß represents an interaction term of M and gender, D represents a dummy variable for the respective community and ε is the stochastic error term, which is randomly distributed across households. Table 4 provides explanations on the outcome

Table 5 Energy use and physical activity during three farming periods by mechanization group and gender

	Manual				*Animal*				*Tractor*			
	M	**F**	**B**	**G**	**M**	**F**	**B**	**G**	**M**	**F**	**B**	**G**
Land preparation period												
Farm PAR	4,5	4,4	4,3	4	3,8	4,1	3,9	4	3,6	2,9	3,8	4,4
Farm share time (%)	22	12	5	5	17	6	10	6	14	5	4	6
Farm share energy (%)	44	29	13	15	34	18	18	15	28	13	13	14
Daily PAR	2,3	2,2	2,2	2,1	2,3	2	2,1	2,1	2	1,8	2,1	2,2
Weeding period												
Farm PAR	4,4	4,7	4,6	4,7	4,5	4,5	4,5	4,6	3,8	4,2	4,5	4,4
Farm share time (%)	24	21	20	20	21	17	20	17	20	16	13	16
Farm share energy (%)	46	41	38	38	38	33	36	34	36	31	25	30
Daily PAR	2,3	2,3	2,5	2,4	2,4	2,3	2,3	2,3	2,1	2,1	2,3	2,3
Harvesting/processing period												
Farm PAR	3,5	3,8	4,2	3,9	4	3,7	4,2	3,9	3,5	3,5	3	3
Farm share time (%)	20	16	13	6	15	15	16	8	16	15	7	10
Farm share energy (%)	34	27	24	11	25	26	27	13	29	25	10	17
Daily PAR	2	2,1	2,3	2	2,4	2,1	2,4	2,2	1,9	1,9	2	2

Males (M), females (F), boys (B), and girls (G). Figures are rounded

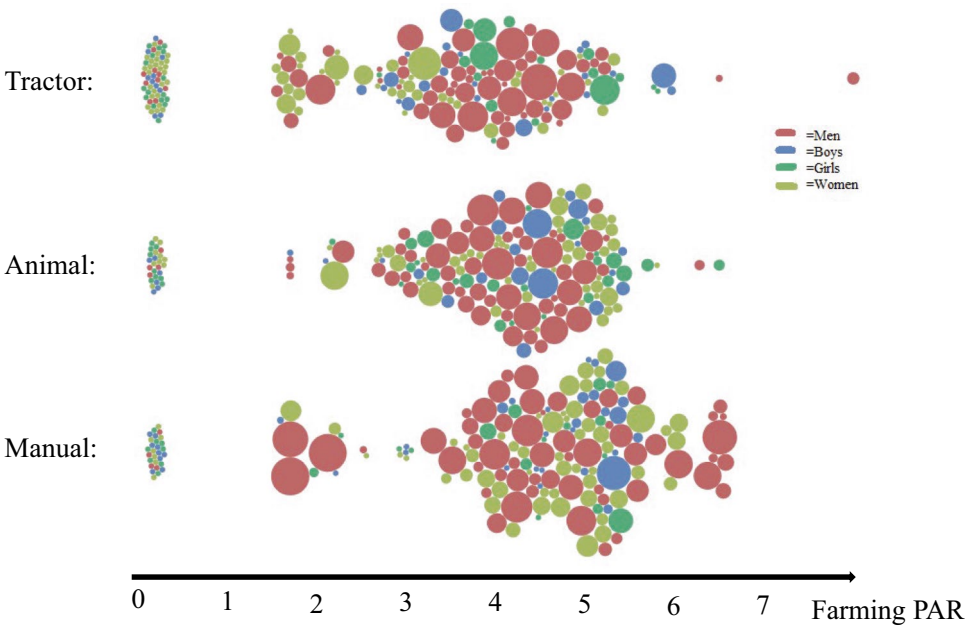

Fig. 3 Farm PAR and time spend farming by mechanization group and gender during land preparation. Note each circle represents one individual. The different rows show individuals from tractor-, animal- and manual-labor-using households, respectively. The position of the circle on the horizontal axis shows the individual's Farming PAR. The size of the circle (radius) represents the individual's time spend farming by gender. The graph was created with https://rawgraphs.io

variables as well as the individual and household covariates, which were selected based on economic theory and include factors that may influence the demand for labor (such as the amount of land cultivated, crop diversity, the number of animals owned and – in the harvesting period—yields) and factors that may substitute for own physical labor (household size, hired labour as well as the use of pesticides and ADP for weed control during the weeding period). The models were estimated with ordinary least squares (OLS) using robust standard errors to account for heteroscedasticity and pairwise correlation coefficients were used to avoid multicollinearity.

3 Results

Table 5 shows the different indicators for energy use and physical activity during the three observed periods: land preparation, weeding, and harvesting/processing. During land preparation, which is the focus of this paper, the table shows that adults in more mechanized households pursue farm activities that are associated with lower physical activity levels (Farm PAR) and spend less time on farming activities (see also Fig. 3). Compared to their counterparts in manual-labor-using households, men and women in the tractor-using households have a Farm PAR that is 25% and 52% lower, respectively, which is significant at the 5% and 1% levels, respectively, using pairwise Tukey-tests. Moreover, men (women) in tractor-using households spend 57% (140%) less time on farming, which is significant at the 10% level.

Taken together this translates into lower non-basal metabolic energy requirements caused by farming. In tractorized households, these values are 57% lower for men and 123% lower for women, than in manual-labor using households. These differences are significant at the 5% level. As a result, male and female adults in tractorized households have significantly lower overall physical activity ratios (Daily PAR) than in households using manual labor (15% and 22% less, respectively). An average male adult would need 533 kilocalories and the average female adult would need 483 kilocalories less per day when using tractors rather than manual labor.[4]

Table 5 also shows that during land preparation, men spend both more time and energy on farming-related activities than women. However, this gender difference seems to become less pronounced during the subsequent seasons. Similarly, the difference between household types (manual labor, ADP, and tractors) becomes less pronounced. In all seasons, and particularly during the weeding season, children spend a significant amount of time and energy on farming. For example, boys and girls in households using manual labor spend around 38% of their non-basal energy on farming activities during the weeding season. There are no clear differences between boys and girls and few differences between children in the different types of households.

[4] To calculate the caloric energy of a stylized average person, daily physical activity ratios were multiplied with typical basal metabolic rates (BMR), which capture the energy needed to ensure cell functions, maintain body temperature, and support cardiac and respiratory muscles as well as brain functioning and are mainly determined by age, gender, height, and weight (FAO et al., 2004). For the calculation of BMR of the stylized persons, the assumptions shown in the appendix 2 were used.

Table 6 shows the share of non-basal metabolic energy requirements caused by different types of activities. This share is determined by the time spent on and the physical intensity of the respective activity. Table 6 not only shows the share for farming but also for the aggregated activity groups transportation, domestic chores, personal care (e.g., sleeping, personal hygiene, and eating), and social life (e.g., resting, chatting, using media). Notable are the high shares of farming, transportation, and domestic chores. Mechanization is related to farming, although differences in time and energy spent on farming may affect time and energy available for other activities, which may be more or less energy demanding. Such substitution effects explain, for example, why the large differences between adults in tractor-using and manual labor using households regarding their non-basal metabolic energy requirements caused by farming (57% for men; 123% for women), translate into much lower differences regarding their daily physical activity ratios (Daily PAR) than households using manual labor (15% for men and 22% for women).

In Table 7, the results of OLS regressions on the relation between the different indicators for energy use and physical activity and mechanization and gender are shown, controlling for the above-mentioned covariates, which may equally affect the demand and supply of physical labor, as well as community effects. Controlling for these factors shows that mechanization and gender as well as their interaction continue to be correlated with energy requirements. During land preparation, which is the mechanized activity studies, tractor-using (ADP using) households spend 18 (11) percentage points less on farming compared to households relying on manual labor. However, this only translated to lower daily PAR for tractor using households who have daily PAR that are on average 0.33 points lower than in manual-labor-using households, which is a significant difference at the 1% level. Overall, this suggests a strong link between the type of farm technology used for land preparation and energy requirements.

To ensure adequate nutrition, differences in energy requirements should be reflected in corresponding

Table 6 Rounded share (%) of non-basal metabolic energy requirements by different activities during different seasons by mechanization group and gender

	Manual				*Animal*				*Tractor*			
	M	F	B	G	M	F	B	G	M	F	B	G
Land preparation period												
Farming & related activities	44	29	15	13	35	18	19	15	28	13	11	15
Transportation	18	13	14	21	27	10	16	19	20	11	21	17
Domestic	3	24	21	17	1	36	12	17	3	29	20	17
Off farm work & seasonal labor	0	0	0	0	0	1	0	0	3	3	0	0
Education	0	0	3	6	0	0	10	4	0	0	3	5
Personal care	20	20	23	21	20	22	21	22	24	26	24	22
Social life	16	13	24	21	17	13	21	24	22	18	20	24
Weeding period												
Farming & related activities	46	41	39	34	38	33	35	35	36	31	25	30
Transportation	16	12	15	15	28	12	14	19	24	13	23	19
Domestic	2	18	12	15	1	26	14	10	1	18	11	13
Off farm work & seasonal labor	0	0	0	0	1	0	0	0	0	2	0	0
Education	0	0	1	0	0	0	1	0	0	0	0	0
Personal care	20	20	19	20	18	20	22	20	23	24	23	21
Social life	16	10	16	15	13	9	14	16	16	12	18	16
Harvesting/processing period												
Farming & related activities	35	27	23	12	25	26	27	13	29	25	13	16
Transportation	21	11	14	16	36	10	18	17	19	9	19	10
Domestic	2	25	17	24	2	28	7	17	3	25	14	20
Off farm work & seasonal labor	0	0	0	1	2	0	0	6	3	1	0	0
Education	0	1	5	8	0	0	3	4	0	0	5	5
Personal care	25	23	22	24	21	25	20	22	25	25	27	26
Social life	17	13	19	16	15	10	23	22	20	15	23	23

Figures are rounded so that they may not always add up to exactly 100

Table 7 Multiple linear regression models with proxies for physical behaviour and energy use by mechanization and gender

Variables	Land preparation period				Weeding period				Harvesting/processing period			
	Farm PAR	Farm share time (%)	Farm share energy (%)	Daily PAR	Farm PAR	Farm share time (%)	Farm share energy (%)	Daily PAR	Farm PAR	Farm share time (%)	Farm share energy (%)	Daily PAR
ADP (dummy)	-0.59**	-4.8	-10.6**	0.03	0.22	0.1	-3.1	0.21**	0.32	-4.2	-8.3*	0.43**
Tractor (dummy)	-0.56*	-8.3**	-18.0***	-0.33***	-0.35	-0.7	-3.6	-0.13	-0.24	-4.0	-6.4	-0.02
Women#Hand	-0.08	-10.2***	-14.6***	-0.10*	0.29	-3.6	-5.6	-0.04	0.29	-4.4	-7.3	0.04
Women#ADP	0.33	-11.1***	-16.2***	-0.22**	0.04	-4.8*	-5.3	-0.15*	-0.25	-0.2	1.2	-0.33
Women#Tractor	-0.76***	-9.1***	-15.7***	-0.12*	0.40	-4.0	-5.1	0.01	0.02	-1.2	-3.7	0.01
Boys#Hand	-0.11	-16.6***	-29.2***	-0.05	0.17	-3.7	-7.7	0.20**	0.67*	-7.1*	-10.8*	0.25**
Boys#ADP	0.17	-7.8*	-16.5**	-0.12	0.09	-1.4	-2.1	-0.06	0.37	0.8	2.2	-0.05
Boys#Tractor	0.22	-9.7***	-17.5***	0.14	0.74**	-6.5**	-8.7*	0.24*	-0.56	-8.2***	-17.3***	0.09
Girls#Hand	-0.50	-17.3***	-31.0***	-0.21	0.31*	-5.5	-9.9*	0.02	0.40	-14.6***	-23.7***	-0.06
Girls#ADP	0.18	-11.2***	-19.2***	-0.12	0.10	-3.7	-2.9	-0.13	-0.02	-7.1**	-11.9**	-0.13
Girls#Tractor	0.82**	-7.9**	-12.8**	0.28	0.63**	-4.8*	-7.5	0.23	-0.50	-7.1**	-13.0*	0.00
Constant	4.22***	20.3***	37.0***	2.27***	4.32***	28.2***	52.9***	2.40***	2.61***	20.4***	30.1***	2.10***
Observations	174	186	186	186	179	181	181	181	164	180	180	180
R-squared	0.35	0.39	0.48	0.23	0.21	0.23	0.25	0.28	0.23	0.26	0.28	0.26

Other covariates are included but are not presented here: land cultivated, TLU, crop diversity, household size, hired labour and community dummies. Additional covariates in the weeding period are the use of 239 pesticides and the use of ADP for weeding. An additional covariate in the harvesting/processing period is yield. The omitted categories are Men#Hand, Men#ADP, Men#Tractor

Table 8 Rounded three-day average daily portions during three seasons by mechanization group and gender

Daily portion sizes	Manual (1)				Animal (2)				Tractor (3)			
	M	F	B	G	M	F	B	G	M	F	B	G
Land preparation period	1,1	1,2	1,3	1,4	1,4	1,5	1,8	1,5	1,4	1,6	1,5	1,6
Weeding period	1,0	1,1	1,2	1,2	1,3	1,3	1,6	1,4	1,3	1,3	1,6	1,3
Harvesting/processing period	1,3	1,4	1,4	1,6	1,3	1,5	1,4	1,5	1,8	1,9	1,8	1,9

differences in caloric intake. As a proxy for caloric intake, portion sizes as reported by respondents were used (see Sect. 2). This made it possible to calculate the average daily portion sizes (see Table 8). Using perceived portions sizes is not without limitations. One is subjectivity: for example, a person may perceive food portions to be smaller on a day where he or she was working very hard. Another limitation is the assumption that larger portions are associated with more calories regardless of what food is eaten. Still, using average portion sizes can be a useful first proxy that indicates whether caloric energy requirements are likely to be met. Tables 8 and 9 shows that individuals in households using animal-draught and tractors, who have one average lower energy requirement, consume more food than individuals in households relying on hand labour, who would need more calories due to hard work. This may be the case because households who need to work less hard are at the same time better off and can afford to eat more, suggesting that food consumption is driven by wealth rather than energy needs.

4 Discussion

Understanding agriculture-nutrition linkages can help to target policy interventions that improve the nutrition of smallholder farmers. So far, these linkages have been studied focusing on the nutritional effects of changing farm yields and farm diversity. In this paper, the focus is on an agriculture-nutrition linkage that has been neglected in the recent literature: the link between farm technologies and caloric energy requirements and, consequently, nutritional outcomes. The results suggest that this agricultural-nutrition linkage is of high relevance for understanding the nutritional status of smallholder farmers. Paying more attention to this forgotten linkage may help to reduce the prevalence of undernutrition among smallholder farmers as well as increase their labor productivity.

Table 9 Multiple linear regressions with daily portions by mechanization group and gender during three seasons

	Land preparation period	Weeding period	Harvesting/processing period
ADP (dummy)	0.30***	0.26***	0.03
Tractor (dummy)	0.29***	0.24***	0.46***
Women (dummy)	0.13	0.01	0.09
Boy (dummy)	0.26**	0.23**	0.08
Girl (dummy)	0.14	0.03	0.11
Constant	1.10***	1.06***	1.31***
Observations	186	181	180
R-squared	0.10	0.12	0.23

Other covariates are included but are not presented here: household size and community dummies

During all farm steps, the daily energy requirements arising from farming were high, which confirms studies highlighting the high caloric energy needs of smallholder farmers (Headey et al., 2012; Kinabo et al., 2003; Rao et al., 2009; Zanello et al., 2017). Depending on the farm step, 3000–3800 kilocalories are needed per day for adult men, exceeding the often-stated average of 2800 kilocalories needed per day. This is in contrast to Srinivasan et al. (2020) who found average caloric energy requirementst between 1900–2500 kilocalories in India and Ghana using accelerometer devises[5] but reflecting early FAO work showing that heavy working adult men need up to 4400 kilocalories per day (FAO, 1957). Such high levels may affect the total time that people can devote to farming: farmers may work less than would be optimal because they do not have sufficient dietary energy to do so. Daily energy requirements were largely determined by farming. During land preparation, farming was responsible for up to 44% of the daily energy need for men and 29% for women. Additional areas requiring much energy were transportation, which is often related to farming, and domestic chores, particularly for women.

Agricultural mechanization is negatively associated with daily energy requirements. Adults in households using tractors for land preparation have 15–22% lower energy requirements than households using manual labor. Individuals in non-mechanized households have higher energy requirements but consume less food and may therefore at least seasonally suffer from undernutrition, especially during the heart of the farming season, which corresponds with the hunger months when last year's harvest dwindles and this year's harvest is not yet ready (Sitko, 2006). Crucially, even in households with mechanized land preparation, energy

[5] Srinivasan et al. (2020) however include data daty with up to three hours of non-wearing.

requirements exceed the FAO recommendation of 2800 kilocalories per day for adult men and 2000 kilocalories for adult women, suggesting that for the Zambian case analyzed here, increasing obesity levels due to the reduction of caloric energy requirements without corresponding diet changes are unlikely. However, this paper focused on peak seasons, and energy requirements may be lower during the lean season. The link between agricultural mechanization, physical activities, and obesity should therefore be carefully monitored given studies showing that smallholder-farming households are not exempt from the double burden of malnutrition (Roemling & Qaim, 2012; Steyn & Mchiza, 2014).

In general, men tend to have higher energy needs than women during the farming steps observed, which confirms findings from Ghana (Zanello et al., 2017). The findings suggest that studies examining gender roles and power relations in farming households should look beyond time-use and adjust for physical activity levels and energy needs, which may make some time-use differences a rational choice. The allocation of tasks, work burden, and food portions may be the outcome of some optimization processes maximizing overall nutritional welfare (Horrell & Oxley, 2012). Similarly, the effects of time-use and energy requirements on children should be considered. During the weeding period, when many children leave their schools to work in the fields, they have daily shares of energy requirements related to farming that are similar to those of adults.

Our study underlines that the collection of data on time-use, physical activity, and nutritional requirements is needed at the individual level (rather than the household level) across the entire farming season. Collecting detailed time-use data from individuals themselves using a smartphone app and then converting such data into energy requirements seems a promising way to do so but some limitations have to be considered. In particular, such a conversion approach does not address the efficiency of movements and intensity of efforts. For example, the approach may neglect intervals of low-intensity and short resting periods. While the Timetracker does capture resting activities, respondents may not have recorded very short resting periods, potentially leading to an overestimation of the energy requirements associated with agricultural activities. Moreover, such conversion approaches also neglect geographic and environmental conditions such as temperature (Ocobock, 2016). As noted in Ainsworth's Compendium (2011), the method also does not account for "differences in body mass, adiposity, age, and sex". Despite these limitations, Limb et al. (2019) suggest that energy requirements calculated using time-use data seem to closely resemble the energy requirements measured with accelerometers. Nevertheless, more research is needed to validate this approach, for example, by using accelerometer devices, which address many of the above-mentioned limitations (Sathiyakumar et al., 2018; Srinivasan et al. 2020; Zanello et al., 2017). However, accelerometer devices enable only limited insights into which type of activities are pursued (e.g. if an activity is related to farming) and more attention needs to be paid to validate the accuracy of accelerometers for farm and rural tasks (Prista et al., 2009). Future studies may combine Timetracker data with energy expenditure data derived from accelerometers for validation and to utilize the strengths of each method. Complementary time-use and accelerometer data may also be used as training data for artificial intelligence software to derive insights into time-use activities based on accelerometer data alone.

The study has some additional limitations. The paper is based on cross-sectional data, which makes it difficult to establish causality, as indicated in the introduction. However, several indications are suggesting that mechanization affects energy requirements – and not vice versa – such as the high share of daily energy requirements determined by farming in non-mechanized households.[6] Future studies may also use compositional regression approaches to better capture the inherent trade-offs between different time-use activities, which may affect the outcome variable "farm share time". However, insights from a prior study using the same time-use data and compositional data (Daum et al., 2021) suggest that this does not undermine the findings. Daum et al. (2021) also find that the "farm share time" during land preparation and weeding are significantly correleated with the degree of mechanization and gender and that "farm share time" during harvesting is significantly correlated with gender. Another limitation is that the study provides only limited insights into the adequacy of calorie intake for individuals in different household categories (manual, animal, and tractor). of the study also neglects nutrition quality. Combining the Timetracker with applications for collecting nutritional data such as the Calculator of Inadequate Micronutrient Intake (CIMI) may be the way forward. CIMI is an app that allows one to record food items consumed and subsequently to assess the levels of energy, protein, and micronutrients absorbed (Wald et al., 2019). Nutritional quality may be important when studying the relation between mechanization and nutritional outcomes because physical activity can influence the absorption of and need for micronutrients (Manore, 2000).

To conclude, agricultural research and policy efforts that focus on agricultural-nutrition linkages need to include the linkage between farm technologies and nutritional outcomes to better understand which agricultural growth pathways contribute most to positive nutritional outcomes,

[6] In principle, energy levels may also affect mechanization. For example, due to death or diseases of households members, the energy available to households may drop, inducing the use of agricultural mechanization.

Appendix 1

Activities	PAR	Ainsworth Compendium Code (AC) / FAO Label - Comments
Farming and related activities		
Land Clearing Manual	6,30	AC08030 "clearing land, … , vigorous effort"
Land Clearing Animal	4,80	FAO "ploughing with horse"
Land Clearing Mechanical	2,80	AC11170 "farming, driving tasks (e.g., driving tractor)"
Hoeing Manual	5,00	AC08241 "… using hoe, moderate-to-vigorous effort"
Ploughing Animal	4,80	FAO "ploughing with horse"
Ploughing Mechanical	2,80	AC11170 "farming, driving tasks (e.g., driving tractor)"
Harrowing Animal	3,84	FAO "ploughing with horse" - 20
Harrowing Mechanical	2,80	AC11170 "farming, driving tasks (e.g., driving tractor)"
Potholing Manual	5,00	AC08050 "digging, spading, filling garden, … "
Ripping Animal	3,84	FAO "ploughing with horse" - 20
Ripping Mechanical	2,80	AC11170 "farming, driving tasks (e.g., driving tractor)"
Ridging Manual	7,80	AC08052 "… ridging, vigorous effort"
Ridging Animal	4,80	FAO "ploughing with horse"
Ridging Mechanical	2,80	AC11170 "farming, driving tasks (e.g., driving tractor)"
Raking Manual	3,80	AC08160 "raking lawn or leaves, moderate effort"
Planting Manual	4,30	AC08145 "planting crops, …, moderate effort"
Planting Mechanical	2,80	AC11170 "farming, driving tasks (e.g., driving tractor)"
Dibbling Manual	3,80	AC08145 "planting crops, …, moderate effort"
Fertilization Manual	3,00	AC 08220 "walking, applying fertilizer or seeding …"
Fertilization Mechanical	2,80	AC11170 "farming, driving tasks (e.g., driving tractor)"
Fertilization Manual Manure	4,80	AC11146 ("…spreading manure…")
Weeding Manual	5,00	AC08241 "weeding…, hoe moderate-to-vigorous effort"
Weeding Animal	4,80	FAO "ploughing with horse"
Weeding Knapsack	4,30	FAO "spraying crops"
Guarding of Crops (Manual)	2,50	AC17085 "bird watching, slow walk"
Irrigation Manual Watering	2,50	AC05148 "watering plants"
Harvesting Manual	4,80	AC11146 "farming, moderate effort e.g., ... harvesting"
Bundling Manual	3,70	FAO "bundling rice"
Drying Manual	1,90	FAO "sorting"
Storing Manual	9,65	FAO "loading 16 kg sack on to a truck"
Bagging Manual	3,90	FAO "bagging and splitting"
Shelling Manual	2,00	AC05050 "…. cooking, de-shelling groundnuts"
Shelling Mechanical	3,80	AC11195 "… grain milling activities"
Manual Grinding/Pounding/Milling	5,60	FAO "pounding grain"
Mech. Grinding/Pounding/Milling	3,80	AC11195 "… grain milling activities"
Winnowing Manual	2,80	Ø Male and Female FAO "winnowing"
Beverage Preparation	2,90	FAO "brewery work"
Marketing	1,50	AC11580 "sitting tasks, light effort … "
Animal Husbandry	4,80	AC11146 "…. feeding animals, chasing cattle …"
Hunting	5,00	AC04100 "hunting, general"
Fishing	3,50	AC04001 "fishing, general"
Gathering	3,50	AC08246 "…picking fruits/vegetables, moderate effort"
Charcoal Making	6,30	AC11110 "coal mining, shoveling coal"
Maintaining Repairing	3,50	Ø AC06127 "home repair… moderate effort" and AC06126 "…light effort"
Farm Administration	1,50	AC11580 "sitting tasks, light effort (e.g., office work)"
Vegetable Garden	3,50	AC08245 "gardening, general, moderate effort"
Cooking Community	2,00	AC05050 "cooking or food preparation … light effort "
Construction Community	4,00	AC11120 "construction, outside, …"
Meeting	1,50	AC11585 "sitting meetings …"
Construction Household	4,00	AC11120 "construction, outside, …"
Off farm work	2,30	AC11003 "active workstation, treadmill desk, walking"
Transportation		
Walking Loaded	5,00	AC11820 "… carrying objects about 25 to 49 pounds"
Walking Unloaded	3,50	AC17190 "walking, 2.8 to 3.2mph, level, moderate pace, firm surface"
Motorbike Loaded	3,08	AC16030 "motor scooter, motorcycle" + 10
Motorbike Unloaded	2,80	AC16030 "motor scooter, motorcycle"
Bicycle Loaded	9,60	AC01030 "bicycling, 12-13.9 mph, leisure, moderate effort" + 20
Bicycle Unloaded	8,00	AC01030 "bicycling, 12-13.9 mph, leisure, moderate effort"
Animal Cart Loaded	2,50	AC16010 "automobile or light truck (not a semi) driving"
Animal Cart Unloaded	2,50	AC16010 "automobile or light truck (not a semi) driving"
Car Van Loaded	1,90	Ø AC16010 "automobile or light truck … driving" and AC16015 "riding in a car or truck"
Car Van Unloaded	1,90	Ø AC16010 "automobile or light truck … driving") and AC16015 "riding in a car or truck"
Bus Loaded	1,30	AC16016 "riding in a bus or train"
Bus Unloaded	1,30	AC16016 "riding in a bus or train"
Tractor Loaded	2,80	AC08055 "driving tractor"
Tractor Unloaded	2,80	AC08055 "driving tractor"
Education	1,80	AC09065 "sitting, in class, general, including note-taking or class discussion"
Care		
Care of children	2,50	AC05184 "child care, infant, general"
Care of sick	3,15	Ø AC05200 "elder care … " and AC05205 "elder care … light effort, …"
Care of old	3,15	Ø AC05200 "elder care … " and AC05205 "elder care … light effort, …"
Household Chores		
Catching water	5,00	AC11820 "… carrying objects about 25 to 49 pounds"
Collecting firewood	3,30	AC08009 "carrying, …. , light-to-moderate effort"
Cooking	2,00	AC05050 "cooking or food preparation … light effort ")
Cleaning	3,30	AC05010 "cleaning, sweeping carpet or floors, general")
Washing pots	2,50	AC05042 "wash dishes, clearing dishes from table, walking, light effort"
Washing clothes	4,00	AC05092 "laundry, hanging wash, washing clothes by hand, moderate effort"
Buying groceries	2,30	AC05060 "food shopping … , standing or walking"
Personal Care		
Sleeping	0,95	AC07030 "sleeping"
Resting	1,30	AC07021 "sitting quietly, general"
Being Sick	1,50	AC13036 "taking medication, sitting or standing"
Eating Drinking	1,50	AC13030 "eating, sitting"
Personal Hygiene	2,00	AC13050 "showering, toweling off, standing"
Social Life		
Media	1,50	AC07025 "listening to music… movie" or AC09055 "phone … text messaging, light effort"
Religion	2,00	AC20020 "standing, singing in church, attending a ceremony, standing, active participation"
Chatting	1,30	AC07060 "reclining, talking or talking on phone"
Sports	7,00	AC15610 "soccer, casual, general"
Dancing/Music/Socializing	3,15	Ø AC03025 "cultural dancing" and AC09100 "retreat … incl. sitting, relaxing, talking, eating"

especially for members of rural households who are vulnerable to undernutrition. While some methodological challenges remain, some tentative policy recommendations can be derived. Promoting agricultural mechanization that saves human energy, including farm mechanization and post-harvest processing, may be a promising pathway to contribute to reducing undernutrition in smallholder farm households, at least in situations that are comparable to the Zambian case study conditions. Institutional solutions such as service provider models may help to ensure access to smallholder farmers to such technologies (Daum & Birner, 2020). From a physical activity perspective alone, tractors are more promising than animal traction. However, it is important to keep in mind that mechanization may affect nutrition through additional agriculture-nutrition pathways, for example, through changes in yield and income, crop diversity, or by making time available for cooking, kitchen gardens, or off-farm work, and that agricultural development has to fulfill other multiple objectives. Beyond farm mechanization, rural mechanization (such as mechanizing transportation and domestic activities) may offer other opportunities to reduce daily energy requirements and undernutrition. From a gender perspective, promoting of technologies for farm activities typically done by women and domestic activities is of particular relevance. Overall, we hope that this case study encourages researchers and practitioners to rediscover the forgotten link between mechanization and nutrition and to use novel approaches to study this link in all its complexity.

Appendix 2

Assumptions for determinants of BMR for average people

Determinant	Men	Women	Boy	Girl
Height (cm)	170	160	160	155
Weight (kg)	65	55	50	45
Age (years)	35	35	16	15
BMR	1559	1307	1442	1296

Heights are average heights of Zambians as measured by Blum and Baten (2012).[7] Weights are expert assumptions. The age reflects the average across our sample. BMR were calculated using http://www.bmi-calculator.net/bmr-calculator/metric-bmr-calculator.php#result. The BMR are based on a stylized woman who is not breastfeeding. With full breastfeeding, daily energy requirements are 675 kcal/day higher; with partial breastfeeding, they are 460 kcal/day higher (FAO et al., 2004).[8]

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Availability of data and material Data is available upon request.

Declarations

Ethical approval and consent The study was conducted according to the guidelines laid down in the Declaration of Helsinki and approved by the Ethics committee of the University of Hohenheim. All study participants gave their written consent to participate in the study. For study participants below the age of 18, consent was obtained from themselves and their parents or guardians.

Conflict of interest The authors declared that they have no conflict of interest.

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