アジア・アフリカ地域研究 第23-1号 2023年9月
Asian and African Area Studies, 23 (1): 26–64, 2023

A Transition in Soil Fertility Management Practices in the Semi-Arid Ethiopian Rift Valley: A Case Study of Agricultural Intensification in Sub-Saharan Africa

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Abstract

Two ethnic groups, the Amhara and Oromo, used distinct soil fertility management practices until the mid-1970s in the northern semi-arid Ethiopia Rift Valley. The Amhara carried compost from their house-yards and applied it to crop fields, whereas the Oromo repeated short-distance transfers (house move) to amend the soil in their vicinity. Soil fertility decline and the introduction of inorganic fertilisers (or chemical fertilisers: IFs) techniques were the primary drivers for the Amhara to change their soil fertility management practices after the mid-1970s. Land constraints caused by population increase, the introduction of IF techniques, and government policy (villagisation) were the primary drivers for the Oromo to change their soil fertility management practices. Since then, their soil fertility management practices merged into what the Amhara had established after the mid-1970s, the combined use of organic fertilisers (OFs) and IFs. Despite the continuous deterioration in the limited availability of animal dung and increasing commuting distances to the crop fields, the adoption rate of the OF techniques and the proportion of manured fields have remained unchanged. A hypothesis of population-induced agricultural intensification in sub-Saharan Africa indicates that future resource constraints can encourage farmers to use more IFs and improved seeds. To enhance the OF-IF integration, OFs technique development of thorough utilisation of organic materials in farmers' vicinity, such as compost techniques, and their dissemination through linkages between research, extension services, and farmers, are the requirements for sustainable soil fertility management in the northern semi-arid Ethiopia Rift Valley.

1. Introduction

Recent studies indicate that the global agricultural production of 2005 needs to increase by 70–100% to meet the rising food demand in 2050 [e.g. Bruinsma 2009], with a wide variety of prospects from pessimism [Mueller *et al.* 2012; Ray *et al.* 2013] to a cautious optimism [e.g.

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Accepted September 30, 2022

Mauser *et al.* 2015; many international organisations reviewed by Tsubota 2016]. In contrast, most researchers are pessimistic about food security in sub-Saharan Africa (SSA) in 2030 [Mason-D'Croz *et al.* 2019] and 2050 (other researchers). In 2050, SSA should feed the population increased approx. 2.5-fold compared with 2005/2007, with an increased demand for cereals approximately triple [van Ittersum *et al.* 2016]. However, it will be challenging to attain this goal by closing the gap between current farm yield and yield potential on existing cropland [van Ittersum *et al.* 2016]. It is because of their small farm sizes and limited market access for most smallholders [Harris and Orr 2014] and intensified soil degradation processes [Pender *et al.* 2006; FAO 2016]. Major areas in SSA experience nutrient limitation as a significant yield gap component [Vanlauwe *et al.* 2014]. Closing maize yield gaps to 50% of attainable yields (approx. 2.3 Mg ha^{-1}) in SSA primarily requires addressing nutrient deficits [Mueller *et al.* 2012]. To overcome low soil fertility problems, most farmers are constrained by a shortage of cash to use inorganic fertilisers (or chemical fertilisers: IFs) partly because farm-level fertiliser prices in SSA are among the highest in the world [Morris *et al.* 2007]. Many medium-term (over five years and more) soil fertility management experiments in SSA suggested that the treatments that combined inorganic and organic inputs showed the best crop yields [e.g. Bedada *et al.* 2014]. Given these contents, integrated soil fertility management, the combined use of organic fertilisers (OFs) and IFs has been enhanced in SSA since the 1990s [Chivenge *et al.* 2011].

In highland temperate and maize-mixed farming systems in Eastern and Southern Africa, including Kenya and Ethiopia, cattle are the most important livestock [Dixon *et al.* 2001]. Cattle manure is an important source of nutrients for crops grown by many smallholders there [Paul *et al.* 2009]. In these parts of SSA, maize is the most or second-most important crop. In SSA, where mixed subsistence- and cash-crop economies prevail, farmers' soil fertility management practices reflect their production choices (subsistence- or cash-crop) [Omamo *et al.* 2002]. Smallholders in Nakuru [Omamo *et al.* 2002] and Vihiga [Waithaka *et al.* 2007] districts, Kenya, use significantly more IFs for cash crops than for subsistence crops (e.g. maize). Part of the Ethiopian highlands, called the maize belt, is Ethiopia's main maize production area, where maize has dual roles, household consumption and sources of cash income; 35% of maize produced was marketed [Gebremedhin *et al.* 2007]. In the maize belt, the adoption rate of IFs was 60% for DAP (di-ammonium phosphate) and 59% for urea in 2001 [Gebremedhin *et al.* 2007], whereas that of OFs was 62% in 2000 [Bacha *et al.* 2004]. The adoption rate and the intensity of IF used for cash crops, such as tef (*Eragrostis tef*) and wheat, have been increasing in Ethiopia. The farmers who applied any IF were 84% and 89% for tef and wheat (averaged over

1995–2004), respectively, across Ethiopia [Endale 2011]. Another survey showed that the intensity of DAP (94% of the total tef farmers used) use increased from 51 kg ha^{-1} to 88 kg ha^{-1} from 2002 to 2012, while that for urea (93% used) increased from 35 kg ha^{-1} to 64 kg ha^{-1} [Minten *et al.* 2013].

Maize production and productivity in Ethiopia doubled between 1990 and 2013. Increases in the adoption rates of improved maize varieties and IFs are the two primary drivers behind this rapid increase in productivity [Abate *et al.* 2015]. Besides, an analysis based on panel data (Ethiopian rural household surveys) collected from 1,520 sample households from the northern Ethiopian highlands, including the maize belt, reported that the farmers' adoption rate of manure increased from 52% in 2000 to 59% in 2002 and 74% in 2005 [Mekonnen and Köhlin 2008]. However, national statistics showed that the maize area covered by OFs declined from 27% in 2004 to 18% in 2013 in Ethiopia [Abate *et al.* 2015]. Several case studies on adopting innovative soil fertility management practices conducted in different Ethiopia measured the proportion of the field areas where OFs and IFs were used.1) If the samples are limited to maize plots: (1) manure and IFs were used at 27% and 67% of the 1,616 maize-legume cropping plots, respectively, sampled from Amhara, Oromia, and SNNPR regions [Teklewold *et al.* 2013]; (2) manure and IFs were applied to 49% and 78% of the 148 maize plots sampled from the Arsi-Negele district (*woreda*), part of the central Ethiopian Rift Valley [Ahmed 2015]; (3) manure and IFs were applied to 59% and 38% of the 480 maize plots, respectively, sampled from eastern Hararge zones, part of the eastern highlands [Ahmed *et al.* 2017]; and (4) compost and IFs were applied to 82% and 2% of the 266 maize plots sampled from the northern semi-arid Ethiopian Rift Valley [Mukai 2017a]. If the samples contain all the randomly selected crop fields: (1) compost and IFs were used at 17% and 24% of the 348 plots, respectively, from the semi-arid Tigray region [Kassie, M. *et al.* 2009]; (2) manure and IFs were applied to 57% and 23% of the 489 plots from the East and West Hararge zones, Oromia [Ketema and Bauer 2011]; and (3) manure and IFs were applied to 25% and 53% of the 1,344 plots from the south Tigray [Hassen 2015]. These findings show that the crop fields where OFs and IFs were used, reflecting local farmers' soil fertility management strategies, are diverse across Ethiopia.

Recently, nine technology adoption studies on the determinants of the farmers' soil

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1) Organic fertilisers (OFs) include manure and compost. Most manure, or animal manure, consists of animal faeces. Meanwhile, compost is a mixture of organic residues (manure, animal carcasses, straw, crop residues, feed refusals) that have been piled, mixed and moistened to undergo thermophilic (high heat) decomposition [Eghball 1997]. However, the case studies picked up here do not necessarily use the definitions of manure and compost properly.

amendment techniques have been conducted in different parts of Ethiopia (Table 1). These studies provided that farmers' soil fertility management strategies are diverse, depending much on the biophysical characteristics of the crop fields, the farmers' socioeconomic endowments, and exposure of the local economy to commercialisation.

This paper describes how farmers in the northern semi-arid Ethiopian Rift Valley have adapted their soil fertility management strategies, part of their indigenous ecological knowledge, to the limited availability of various natural resources and sociopolitical changes since the 1970s. To this end, all the aforementioned case studies on the determinants of the farmers' soil amendment techniques have two difficulties. First, they targeted the present phenomena. Thus, other approaches that compare before and after would be required. Second, they all take only econometric approaches. However, the econometric models that value the reciprocal relationships (complementarity or substitutability) between two soil amendment options, e.g. the instrumental variable or multivariate probit analyses, cannot distinguish the sources of the potential simultaneity bias of adoption decisions [Belderbos *et al.* 2004]. This made it difficult to compare the analyses conducted in different environments or periods and to understand the sources of the complementary or substitute relationships between OF and IF use in the respective studies [Mukai 2023].

Therefore, this study collected two temporal datasets, (i) before the mid-1970s and (ii) at the time of the field survey in 2012, from two major maize production zones in the northern semi-arid Ethiopian Rift Valley using remote sensing, household surveys, and interviews. In the area where quantitative research methods [Cohen *et al.* 2007] can use, the econometric models were formulated for the before-the-mid-1970s and 2012 datasets. The model considered the potential simultaneity between OF application and IF use. Meanwhile, in the area where quantitative research methods cannot use, qualitative research methods [Cohen *et al.* 2007], i.e., field observations and careful interviews with farmers, were used. The qualitative research methods also help explain the background of the econometric analyses. Mixed methods (quantitative and qualitative) used in this study may have a more persuasive power to compare the differences in the farmers' determinants in different environments and periods, therefore, more policy implications.

This study addresses the following research questions: what was the farmers' indigenous knowledge of soil fertility management practices? How have farmers changed their soil fertility management practices? What were the drivers of the changes? What types of soil fertility management practices will they select against the unfavourable changes in various resources and commercialisation in crop production?

Table 1. Signs and Statistically Significant Levels of the Independent Variables Used in Recent Technology Adoption Studies in Ethiopia

	1) Benin [2006]				2) Pender & Gebremedhin [2006]		3) Marenya & Barrett [2007]		4) Kassie, M. *et al.* [2009]		5) Ketema & Bauer [2011]		6) Teklewold *et al.* [2013]		7) Ahmed [2015]		8) Hassen [2015]		9) Ahmed *et al.* [2017]	
	House hold wastes	Manure	IF																	
			LP[b]	HP[b]	OF	IF	OF	IF	OF	IF	OF	IF	OF	IF	OF	IF	OF	IF	OF	IF
Gender	+	+	+	+	$+^{**}$	+	$+^{**}$	$+^{*}$	−	+	−	+	$-^{*}$	+	n.u.	n.u.	+	+	−	$+^{*}$
Off-farm	−	+	+	−	−	−	$+^{***}$	$+^{*}$	n.u.	n.u.	n.u.	−	+	−	−	+	−	$+^{***}$	n.u.	n.u.
Farm	+	−	−	$+^{***}$	−	$-^{**}$	$+^{**}$	$+^{*}$	+	+	+	+	$-^{c}$	$+^{***c}$	−	−	$+^{c}$	$+^{***c}$	−	$+^{**}$
Livestock	$+^{***}$	$+^{**}$	+	$-^{***}$	$+^{***}$	$+^{**}$	$+^{*}$	$+^{**}$	$+^{**}$	$+^{***}$	+	$+^{**}$	+	$+^{***}$	$+^{**}$	−	$+^{***}$	n.u.	$+^{***}$	$-^{***}$
Labour	$-^{***}$	$-^{**}$	+	+	−	−	$+^{***}$	$+^{**}$	+	−	$+^{*}$	n.u.	n.u.	n.u.	+	$-^{*}$	$+^{***}$	+	n.u.	n.u.
Market[a]	$-^{d}$	$+^{***d}$	$-^{d}$	$+^{d}$	$+^{e}$	$+^{e}$	n.u.	n.u.	+	−	n.u.	+	−	−	−	+	+	−	n.u.	n.u.
Plotsize	−	−	+	$+^{***}$	n.u.	n.u.	n.u.	n.u.	n.u.	n.u.	$+^{***}$	$+^{***}$	n.u.	n.u.	+	$+^{*}$	−	+	n.u.	n.u.
Distance	$-^{***}$	$-^{***}$	−	$-^{**}$	$-^{***}$	$-^{**}$	n.u.	n.u.	+	$+^{**}$	$-^{*}$	+	−	−	−	$-^{**}$	$-^{***}$	−	−	−

Note: $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$, n.u.; not used.

[a] *Market* indicated the distance to the nearest market.

[b] LP; Low potential areas, HP; High potential areas.

[c] The total value of assets represented the sample farmers' wealth level.

[d] Distance to the nearest input supply shop represented.

[e] Distance to the nearest district (*woreda*) town represented.

2. Materials and Methods

2.1 *Study Area*

The uppermost reaches of the Tebo and Geldia seasonal river catchments area (265 km^2) are in the Tebba Gersa mountainous area on the southeastern edge of the central Ethiopian highlands (true highland area; 2,100–2,200 m above sea level, with annual rainfall 1,000–1,200 mm; Fig. 1). Other parts of the catchments area (the study area) are located within the northern semi-arid Ethiopian Rift Valley. Most of the Tebo-Geldia catchments area is in the Boset district, Oromia region. Northern semi-arid Ethiopian Rift Valley is categorised into the following two sub-areas in terms of the major maize production zones in Ethiopia: mid-altitude dry (1,000–1,600 m above sea level, annual rainfall 650–900 mm) and mid-altitude moist (similarly, 1,700–2,000 m, 1,000–1,200 mm) sub-areas [Abate *et al.* 2015].

Of the nine major crops of the Boset district, maize, sorghum, wheat, barley, lentils, horse beans, and field peas are used mainly for house consumption (54–76% of the total usage; Table 2),[2)] while tef and haricot beans are primarily used for income sources (57–78%). The major crops in the mid-altitude moist sub-area and true highland area in the catchments area are wheat, tef, and maize, whereas those in the mid-altitude dry sub-area are sorghum, tef, and maize [ICRA

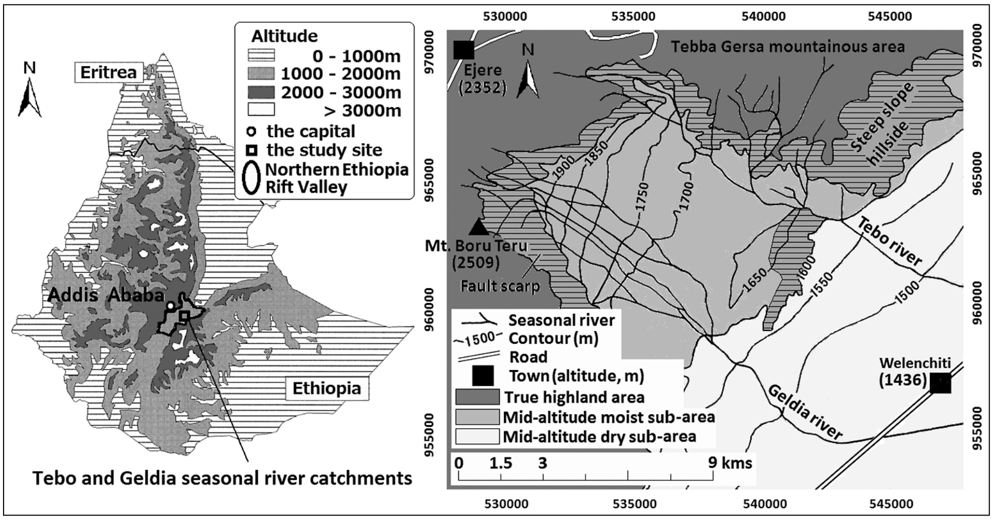

Fig. 1. Ethiopia and the Semi-Arid Northern Ethiopian Rift Valley (Left Figure), and the Tebo and Geldia Seasonal River Catchments, the Study Area (Right Figure)

Table 2. Crop Utilisation of the Major Crops in Boset District, Oromia Region, in 2002

Crop	Cultivated area (ha)	Percent utilised for (%)		
		House consumption	Sale	Others
Maize	14,512	73	13	14
Tef	10,568	27	57	16
Haricot beans	4,779	11	78	11
Sorghum	4,016	76	15	9
Wheat	952	62	7	31
Barley	882	54	10	36
Lentils	293	76	19	5
Horse beans	66	70	14	16
Field peas	7	61	18	21

Note: Others include seed, wages in kind, and animal feed.
Source: The author's calculation based on CSA [2003].

1999]. The nine major crops and rainfed vegetable fields are mixed in both sub-areas.

The primary ethnic group living in the true highland area is the Amhara. The Oromo is the primary ethnic group in the mid-altitude dry sub-area, except for town areas like Welenchiti. The Amhara and Oromo live juxtaposed in the mid-altitude moist sub-area between the true highland and mid-altitude dry sub-area. Mekonnen [2013] portrayed the sedentary lifestyle of the Amhara; fertile volcanic soil combined with generous rainfall and a cool and brisk climate provided the Amhara with a stable agricultural and pastoral existence in the Ethiopian highlands. In contrast, the Oromo are believed to have adhered originally to a pastoralist/nomadic and/or semi-agriculturalist lifestyle [Mekonnen 2013].

Ethiopia has been described as one of the most severely affected countries by soil erosion [Haregeweyn *et al.* 2015]. A study on soil nutrient balance at a plot level conducted in the northern semi-arid Ethiopian Rift Valley showed nitrogen and phosphorus deficits [Yimer and Abdelkadir 2010]. Northern semi-arid Ethiopian Rift Valley is the most drought-prone part of Ethiopia, with high rainfall variability during the rainy season [Segele and Lamb 2005] (Fig. 2). Projections for future climate suggest that annual rainfall will change by -40 to +10%, and the annual temperature is expected to increase in the range of 1.4 to 4.1°C by the 2080s [Kassie *et al.* 2014a]. Accordingly, simulated water-limited maize potential yield for early maturing

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2) A fermented dough of maize, sorghum, and barley is used for cooking *injera* (a thin, fermented Ethiopian bread). Maize and sorghum are also used for brewing. Wheat flour is used for cooking *dabo* (Ethiopian bread). Beans and peas are used for cooking *wot* (Ethiopian stew).

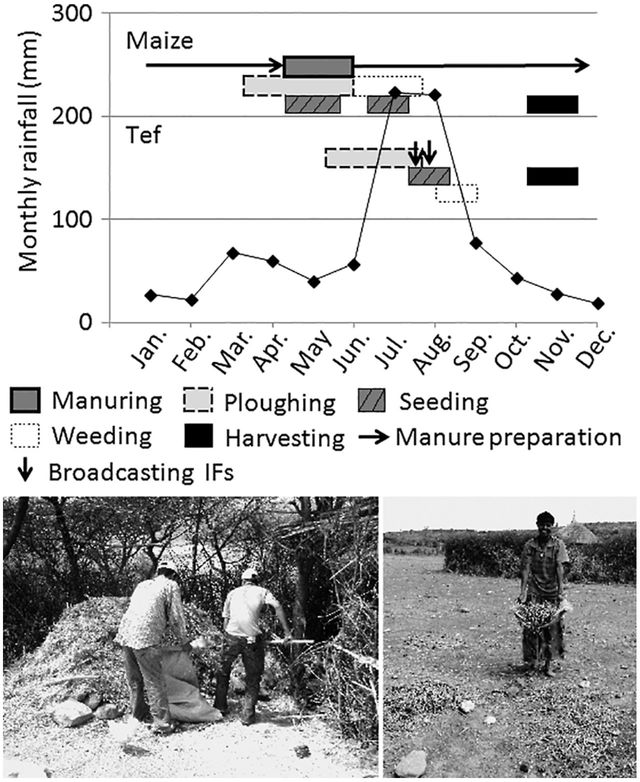


Fig. 2. Cropping Calendar (Upper) and Farmer's OFs Application Practices (Lower)
Farmers were Going to Carry Compost (*Kosi*) from a Pile to an *Arada* Field (Left Photo), and A Housewife was Going to Dump House Wastes onto an *Arada* Field (Right Photo)
Source: Monthly mean rainfall data is from the Welenchiti rainfall gauge (1992–2013).

cultivars would decrease by approx. 8% [Kassie *et al.* 2014b]. The balance between the population, livestock numbers, and natural resource reserves will likely worsen in the northern semi-arid Ethiopian Rift Valley [Meshesha *et al.* 2012]. The soil fertility decline in the semi-arid Ethiopian Rift Valley is likely to continue further [Yimer and Abdelkadir 2010].

2.2 *Narrative Inquiry Interviews*

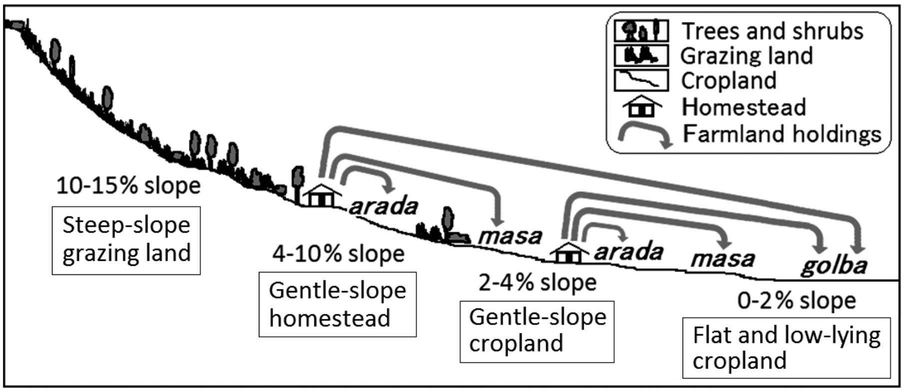
In 2011, narrative inquiry interviews were held with elderly farmers (three individuals for the mid-altitude moist sub-area and four individuals for the mid-altitude dry sub-area) to ascertain the research subjects: (i) history of village formation; (ii) land use/cover changes; (iii) changes in cropping systems and farming practices; and (iv) changes in soil fertility management practices by a narrative inquiry method [Clandinin and Huber 2002] (Table 3). The interviewees with rich

Table 3. Research Subjects and Sample Interview Questions in the Narrative Inquiry Interviews

Research subjects	Sample interview questions
History of village formation	Can you please tell us your paternal family's history of migration and settlement? Who were the pioneer settlers of this village?
Land use/cover changes	Please tell us about the land use/cover changes in your village. When were the croplands of your ancestors established?
Changes in cropping systems and farming practices	Please tell us if you have experienced any temporal changes in your cropping system, e.g., the field types (*arada*, *masa*, and *golba*), crops cultivated, and crop sequences. Were there any resource constraints or socio-political changes that influenced changes in the cropping system?
Changes in soil fertility management practices	Have you experienced any changes in soil fertility management practices? Were there any technological advances that impacted soil fertility management practices?

information on village formation and farming knowledge and experience were selected purposefully [Baxter and Eyles 1999]. A snowballing sampling strategy [Patton 2002], in which interviewees suggested other potential participants, was used to identify and select information-rich cases. The seven recorded interviews were transcribed into written English. Initial codes were created based on the emerging patterns in the transcribed texts [Cope 2003], which were often commonly seen in the texts from both the sub-areas. Moreover, to dig deeper into the processes, secondary codes were generated based on the frequency of appearances in the texts, which were often distinctively different between the two sub-areas.

The narrative inquiry interviews found that farmers categorise crop fields into *arada*, *masa*, and *golba* (Fig. 3). Farmers dichotomise *arada* and *masa* fields regarding their relative soil fertility levels. Farmers apply OFs (compost and household wastes) to *aradas* (the plural form of *arada*; Fig. 3). It improves soil chemical properties (significantly increases soil organic carbon, total nitrogen (N), phosphorus (P), cation exchange capacity, K, Na, Mg, electric conductivity, and NO_3-N and significantly lowers pH [Mukai 2019]). It also improves soil physical properties (significantly reduces soil compaction and bulk density and significantly increases porosity) compared to those in *masa* fields [Mukai 2019]. With few exceptions, *aradas* are located adjacent to homesteads, whereas *masas* (the plural form of *masa*) are away from homesteads (Fig. 3). Most households hold continuously cropped maize fields in *aradas* because maize yields are significantly affected by soil fertility levels, particularly N and P [Debelle *et al.* 2002]. Farmers harvest the upper half of the maize stalk early for feed. They sometimes harvest it in September,



Cropping systems		Main crops	Field types	Soil fertility management practices	
				Before the mid-1970s	In 2012
SCCS	Continuous maize cultivation	Maize, barley	*Arada*	Continuous OFs application	[1] Continuous OFs application or [2] no soil amendment on *ona* (previous *arada*)
	Continuous sorghum cultivation	Sorghum, maize	*Golba*	No soil amendment because *golba* soils are fertile	Same as on the left
CCCS	Cash crops and subsistence crops are rotationally cultivated	Cash crops (tef, haricot bean, rainfed vegetables), subsistence crops (sorghum, wheat, barley, beans, peas)	*Masa*	[1] No soil amendment or [2] occasional OFs application	[1] Only IFs use or [2] IFs use and an occasional compost application

Fig. 3. Micro-Topography, Land Use, Field Types, Cropping Systems, and Soil Fertility Management Practices before the Mid-1970s and 2012 in the Northern Semi-Arid Ethiopian Rift Valley

Note: SCCS; subsistence crop-based cropping system, CCCS; cash crop-based cropping system, OF; organic fertiliser, IF; inorganic fertiliser. Flat and low-lying cropland and *golba* can be seen only in the mid-altitude dry sub-area. Arrows indicate farmland holdings.

not waiting for its maturing stage from October to November, to eat raw (Fig. 2). For poor farmers, maize is significant as emergency food to weather a food shortage in the slack season. Farmers cultivate barley when the soil fertility of an *arada* is declined. In contrast, other subsistence crops (sorghum, wheat, barley, beans, and peas) and cash crops (tef, haricot beans, and rainfed vegetables) are rotationally cultivated in relatively unfertile *masas*. Some crop fields are situated in the flat and low-lying cropland areas, and their soil fertility is maintained by the inflow of fertile soil from the upper-reach fields during the rainy season. This field is referred to as *golba*. *Golba* is only observed in the mid-altitude dry sub-area, located at the lower reaches of the Tebo and Geldia seasonal river catchments (Fig. 1). Farmers cultivate maize and sorghum in a fertile *golba* (Fig. 3).

Compost (*kosi*) is made from various locally available organic materials, such as animal dung, kitchen ash, crop residues, and feed refusals (Fig. 2). These compost materials are piled up in the corners of house-yards for several months to a few years for decomposition [Mukai and Oyanagi 2019]. A housewife mainly collects these organic materials through house-yard sweeping and dumps them onto a compost pile. Farmers carry compost from the compost piles to fields from April to June before crop seeding and scatter it on the ground. The compost is incorporated into the soil by subsequent ploughings [Mukai 2018]. Household wastes are of substantially various compost feedstock materials [Mukai and Oyanagi 2021], collected through house-yard sweeping and dumped directly onto a backyard maize field every few days (Fig. 2).

The narrative inquiry interviews also found that, around the 1870s, the Amhara and Oromo pioneers migrated from the Ethiopian highlands to the sub-areas. They exploited the forest to settle there. The interviews also showed that the practice of OFs (compost or household wastes) application was popular even before the mid-1970s in the mid-altitude moist sub-area among the Amhara. Even before the mid-1970s, they had distinct relationships between the field types (*aradas* and *masas*) and cropping sequences, similar to those observed now. In the 1950s, grain marketing was well-developed, even in rural areas in Ethiopia [Holmberg 1977]. Tef has been cultivated mainly for selling in both the sub-areas since the 1950s at the latest. The government introduced IF techniques during the latter half of the 1970s. Since then, farmers in the northern semi-arid Ethiopia Rift Valley began using IFs on *masas* mainly for cash crop cultivation. In contrast, the interviews showed a significant change in the relationships between the field types, cropping sequences, and soil fertility management practices that had occurred in the mid-altitude dry sub-area among the Oromo after the mid-1970s. It was a transition period from the Haile Selassie Imperial era (1930–1974) to the Derg socialist regime (1974–1991).

Thus, in the mid-altitude moist sub-area, this study focused on comparing (i) the determinants of soil fertility management practices (OFs application and IFs use) in the fields and (ii) some key resource indices (e.g., household farm size, livestock ownership, adoption rates of OF techniques, areas of OFs application) before the mid-1970s and 2012. Towards those ends, quantitative research methods were mainly used. In contrast, in the mid-altitude dry sub-area, this study examined how the Oromo adapted their indigenous soil fertility management practices to resource constraints and sociopolitical changes since the mid-1970s. For this purpose, qualitative research methods were mainly used.

2.3 *Quantitative Research Survey*

A structured questionnaire survey was conducted in the mid-altitude moist sub-area in 2012. The sub-area consists of two villages (*kebele*). Sample plots and household heads who held the sample plots were selected randomly from the two villages. For the dataset before the mid-1970s, 199 plot data were collected from 103 households, while for the 2012 dataset, 282 plot data were collected from 142 households. These sampled household numbers in the mid-1970s and 2012 datasets and sampled plot numbers in the 2012 dataset statistically correspond to respective confidence intervals of 8.5%, 7.6%, and 5.7% under a 95% confidence level, compared to the estimated household and plot numbers in the two villages at the correspondent times.3)

When asking about the farmers' soil fertility management practices before the mid-1970s, consideration was given to the interviewees' ages and home villages. If the interviewees were in their late 50s at the interview, i.e. they had reached 20 years of age in the mid-1970s, their own experience was ascertained. In contrast, if the interviewees had not reached that age yet, they were interviewed about their parents' soil fertility management practices. If their parents migrated from other maize production zones, their parents' experiences in farming after migrating to the present area were assessed.

The questionnaire survey dataset before the mid-1970s was analysed using binomial logit models. Adoption studies of soil amendment options (e.g. OF or IF use and OF and IF use) appeared in literature in the early 2000s, and case studies on SSA dominate it [Mukai 2017a]. Among those, econometric models that are usually used to predict a binary dependent variable (i.e. OFs were adopted or not adopted, or IFs were adopted or not adopted) were binomial logit [Somda *et al.* 2002; Mkhabela and Materechera 2003] or binomial probit [Abdoulaye and Sanders 2005]. Because OFs use was only soil management practice in the study area before the mid-1970s, the dependent variable (*man*) used for the binomial logit models represented whether OFs were applied (*man*=1) or not (*man*=0; Table 4). Independent variables (Table 4) were determined by referring to previous adoption studies on soil fertility management practices in

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3) In Ethiopia, population censuses were conducted in 1984, 1994, and 2007. District (*woreda*) level population data is available over the three years, and village-level population and household numbers are available from the 1994 and 2007 censuses [CSA 1984; 1994–1997; 2010]. Using the rural population data in 1984, 1994, 2005, 2007, and 2014 (the government projected those in 2005 and 2014 [CSA 2005; 2013]), the total household numbers in the two villages in 1975 and 2012 were estimated. Using the mean plot number held by a household in the northern semi-arid Ethiopian Rift Valley in 2012, 5.7 [Mukai 2023] and the estimated total household number, the total plot number in the two villages in 2012 was estimated.

Table 4. Dependent and Independent Variables for Econometric Analyses and Summary Statistics of the 2012 Dataset

Dependent variables	*Man* (binary): 1=Organic fertilisers (OFs) were applied, 0=not applied *Fer* (binary): 1=Inorganic fertilisers (IFs) were used, 0=not used	OFs were applied or not (*man*)			IFs were used or not (*fer*)		
		Applied	Not applied	*p*	Used	Not used	*p*
Independent variables (1) Household attributes	[1] HH (household head) *gender*[a] (binary): 1=male, 0=female	0.86	0.79	*ns*	0.84	0.84	*ns*
	[2] HH *ethnic* group (binary): 1=the Oromo, 0=the Amhara	0.09	0.17	*	0.13	0.11	*ns*
	[3] HH *tenancy* (binary): 1=landlord, 0=tenant	No data			No data		
	[4] *Education* expresses the number of years the HH spent in a school (year)[b]	1.2	0.7	**	1.0	1.0	*ns*
	[5] *Farm* is the total cropland size held by the HH (ha)	2.2	1.8	**	2.0	2.0	*ns*
	[6] *Labour* is the total family and regular labour force converted to an adult (from 16 to 65 years old) labour force equivalent (persons)	3.9	3.4	**	3.7	3.7	*ns*
	[7] *Livestock* represents: livestock ownership level (TLU)[c]=Cattle ownership level (TLU) × (1−*Fuel* (%)/100)+other livestock ownership level (TLU)	3.7	2.4	***	3.2	3.3	*ns*
	[8] *Donkey* represents the ownership level of donkey and camel (heads)	1.4	1.1	***	1.3	1.3	*ns*
	[9] *Fuel* means the percentage of the household's cattle dung consumed for fuel (%)	32	34	*ns*	33	32	*ns*
(2) Plot attributes	[10] *Crop* means the main cropping system to which the sample plot belonged: 1=CCCS, 0=SCCS	0.31	0.84	***	1.00	0.00	***
	[11] *Plotsize* represents the size of the sample plot (ha)	0.22	0.25	***	0.26	0.19	***
	[12] *Distance* is the commuting distance to the sample plot (m)	203	857	***	726	145	***

Note: [a] Italics are variable names.

[b] Adult education was counted to be 0.5.

[c] TLU, Tropical livestock unit.

SSA [Mukai 2017a]. All the independent variables were grouped according to whether the OFs were applied. For binary and numerical variables, *t*-tests and Pearson's chi-square tests were used to detect differences in the means of the variables between the binary choices in *man*, respectively.

Among the independent variables selected, the land tenancy of the household head (*tenancy*) is used only for the before-the-mid-1970s dataset. During the Haile Selassie Imperial regime (1930–1974), the land was owned by tiny feudal landlords, and most farmers were their tenants. The Derg socialist regime (1974–1991) that overthrew the imperial regime adopted a socialist mode of government. They abolished landlord-tenant relations, nationalised all rural land, and redistributed it to farmers.[4] The Derg regime also implemented the villagisation policy, which started in 1985. The villagisation aimed at an agglomerated rural settlement, permanently removing villagers from their ancestral lands.[5]

Because OFs application and/or IFs use were standard soil amendment options after the mid-1970s, the 2012 questionnaire survey dataset was analysed using the bivariate probit model. Several adoption studies have recently analysed a reciprocal relationship (complementarity or substitutability) between OFs and IFs use in SSA. They used instrumental variable analysis [Benin 2006; Pender and Gebremedhin 2006; Ketema and Bauer 2011] or multivariate probit analysis [Marenya and Barrett 2007; Kassie *et al.* 2009; Teklewold *et al.* 2013; Ahmed 2015; Hassen 2015; Kassie *et al.* 2015; Ahmed *et al.* 2017]. A variable *man* represents household heads' binary choices of OF adoption (*man*=1) or no adoption (*man*=0) in the plot (Table 4). In contrast, variable *fer* denotes IF adoption (*fer*=1) or no adoption (*fer*=0).

Mukai [2023] analysed the farmers' determinants of soil fertility management practices using 524 plot data collected from the semi-arid northern Ethiopian Rift Valley. He hypothesised that the plot data were categorised into two groups representing the subsistence-crop-based cropping system (SCCS; 266 plot data) and the cash-crop-based cropping system (CCCS; 258 plot data). A data segmentation approach and a dummy variable method were used to incorporate the structure of a local farming system into econometric models. Based on the K-means cluster

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[4] The landholding structures did not change much before and after the implementation [Fassil 1993:132–133]. Since then, the Ethiopian government has advocated state ownership of land whereby only usufruct rights are bestowed upon landholders. The usufruct rights exclude selling or mortgaging the land [Crewett *et al.* 2008].

[5] The villagisation program was intended to facilitate the delivery of social services like health and education to the people by clustering the settlement of villagers [Geda 2018]. In the mid-1980s, deep tubewells were constructed with the help of international donors at the village level in the Boset district. This also helped cluster the settlement of villagers because people were relieved from going to communal ponds or the Tebo River to fetch water.

analyses (K=2), the two subdatasets representing SCCS (250 plot data) and CCCS (274 plot data) were created. The following four bivariate probit models were formulated: (i) model 1 used the pooled dataset with independent variable *crop* (cropping system to which the sample plot belonged; 1=SCCS, 0=CCCS), (ii) model 2 used the pooled dataset without *crop*, (iii) model 3 used the SCCS subdataset, and (iv) model 4 used the CCCS subdataset. Models 3 and 4 are based on the data segmentation approach, while model 1 represents the dummy variable method. Model 2 is with the conventional approach, not considering the structure of the pooled dataset. Several goodness-of-fit (i.e., how well the model fits into a set of observations) tests validated that it is better to analyse each subdataset separately using models 3 and 4 than analysing the pooled dataset. Exogeneity tests showed that the household heads considered their OF and IF use independently. This study considered employing these approaches. Stata 13.0 (StataCorp LP) was used to perform the binomial logit and bivariate probit analyses [Cappellari and Jenkins 2003], while SPSS ver. 20 (IBM) was used for the other statistical analyses.

2.4 *Qualitative Research Methods*

A field database was created targeting a 27.6 ha area near Merko hamlet, Merko Odalega village, Boset district, to ascertain the changes that occurred for the Oromo in the mid-altitude dry sub-area. This target area included homesteads for 20 households (6.4 ha in total) and 79 plots (4 *aradas* and 75 *masas*; 21.2 ha in total) held by 33 household heads at the time of the survey. Information on (i) the establishment periods of the plot and (ii) land use/cover, (iii) landholder, cultivator, field type, cropping sequence, and soil fertility management practice during each period of the Haile Sellasie Imperial regime (1930–1974), the Derg socialist regime (1974–1991), and 2012 were fed into the field database. A structured interview was conducted in 2012 with 43 individuals to create the database. These individuals were descendants of the household heads who had held land or currently had land in the 27.6 ha target area since the 1950s.

Information on land use/cover was obtained from the interview and aerial photos taken in 1957, 1972, and 2005. Orthophotographs (1:50,000) were created from the 2005 aerial photos. The geometric rectification of the 1957 and 1972 aerial photographs was performed by co-registration with the 2005 orthophotograph [Mukai 2017b]. Using ArcGIS 10.1 (ESRI), land use/cover changes between three periods (1957, 1972, and 2005) were digitally mapped. Enlarged aerial photos from 1957 (representing the mid-Imperial period) and 1972 (representing the late-Imperial period and a transition period from the Imperial to the Derg periods) and a chronology were prepared for the interview. During the interview, these were shown to the informants as reference materials. They helped ascertain the establishment periods of the plots and the starting years of their OF and IF use. It was because, on the 1:50,000 aerial photos, plot boundaries with the downslope ones, which often form soil or stone bunds, are seen. When ascertaining the positions of crop fields (plots), grazing lands, and homesteads in the past, an accurate global positioning system (GPS; Trimble GEO XT 2008 series) with planimetric and altimetric accuracies at the sub-meter level was used. The location data acquired from the GPS were positioned on the digital map using ArcGIS.

A semi-structured interview and field measurement were also conducted in the mid-altitude dry sub-area with the informants who participated in the structured interview. Interview questions asked in the semi-structured interviews were based on the secondary codes generated in the narrative inquiry interview and the literature on traditional knowledge (TK; Table 5).[6] For less-structured interview questions asked in the semi-structured interviews (e.g. questions 1-1-2, 2-1-1, and 2-1-2 in Table 5), unrecorded interviews were noted down in field notes, which were transcribed. The same coding process taken in the narrative inquiry interviews was adopted to generate key themes.

A structured interview and field measurement were conducted in 2012 with one male household head, Teshome Yadete (aged 68 at the interview), to visualise the changes in soil fertility management practices in the mid-altitude moist sub-area. A field database was created, into which information on the boundaries with surrounding fields, cropping sequence, and soil fertility management practice of each crop field, held by Teshome Yadete in the mid-1950s, at the beginning of the 1970s, and in 2012 was input.

3. Results and Discussion

3.1 *Changes in Determinants of Soil Fertility Management Practices in the Mid-Altitude Moist Sub-Area*

For the quantitative research survey, 199 plot data and 282 plot data were collected from the

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[6] TK is the "cumulative body of knowledge, practice, and values acquired through experience and observations on the land and handed down from generation to generation" [Pearce *et al.* 2015]. Many studies examined the role of TK in adaptation to diverse and changing socioeconomic and environmental conditions, including climate change [e.g. Anderson *et al.* 2018]. Reviewing previous TK studies, Pearce *et al.* [2015] conceptualised the role of Inuit (indigenous communities in Canada's subarctic) TK in adaptation to climate change as exposure sensitivities, adaptive capacity (or resilience), and adaptations. Exposure sensitivity is a joint property of the TK system's characteristics and socioeconomic and environmental stimuli characteristics. Adaptive capacity refers to the underlying socioeconomic and political drivers influencing how an individual or community experiences change and their capacity to adapt. TK contributes to adaptive capacity in changing socioeconomic and environmental conditions [Pearce *et al.* 2015].

Table 5. Secondary Codes and Key Themes Emerged from the Narrative Inquiry Interviews and Sample Questions in the Semi-Structured Interview in the Mid-Altitude Dry Sub-Area

Secondary codes and key themes	Sample interview questions (examples)
1) Oromo traditional soil fertility management practices (Oromo TK) 1-1) House move 1-2) Household wastes input 1-3) Kraal move 1-4) Crop rotation in the field	1-1-1) History of your or your father's/mother's homestead moves (location and area). 1-1-2) Why and how did you move the homestead? 1-2-1) Where did you apply household wastes? 1-3-1) Was kraal move a popular soil fertility management practice for you? 1-4-1) Did you cultivate crops rotationally?
2) Changing conditions that affected the Oromo indigenous soil fertility management practices (exposure sensitivity) 2-1) Scarcity of the land suitable for the house move 2-2) Derg villagisation policy 2-3) Introduction of IF and compost techniques	2-1-1) When and why did you or your father/mother stop the homestead move? 2-1-2) When and why did you stop the kraal move? 2-3-1) Have you perceived soil fertility decline in the field since the mid-1970s? If yes, where did you perceive it? 2-3-2) When did you or your father/mother begin compost making and application?
3) Adaptation to the changing conditions (adaptive capacity and adaptations) 3-1) Long-term settlement and sedentary life 3-2) Assimilation into the Amhara cropping systems and soil fertility management practices	3-1-1) How did the homestead structure differ before the mid-1970s and the present? 3-2-1) When did the distinction of the fields between *arada* and *masa* begin? 3-2-2) Do you apply compost rotationally to some *masa* fields?

Note: Secondary codes and key themes corresponded to the components of traditional knowledge (TK).

mid-altitude moist sub-area for the before-the-mid-1970s dataset and 2012 dataset, respectively. The narrative inquiry interviews found that both datasets could be divided into two cropping systems in terms of the relationship between field types (*arada* or *masa*, which represents soil types, soil fertility levels and slopes), crops cultivated and crop sequences, farmers' tendency to use crops (for house consumption or selling), and soil fertility management practices (Fig. 3). One can be called a subsistence-crop-based cropping system (SCCS), where maize (and sometimes barley) is continuously cultivated in a fertile *arada*. Both crops are mainly used for house consumption (i.e., subsistence crops). The SCCS contains 96 samples in the before-the-mid-1970s dataset and 140 samples in the 2012 dataset (Table 6). Another can be called a cash-crop-based cropping system (CCCS). In the CCCS field, cash crops (i.e., crops mainly used for selling), such as tef, haricot bean, and rainfed vegetables, and subsistence crops, such as barley, wheat, beans, and peas, are rotationally cultivated in *masas*. The CCCS contains 103 sample

Table 6. Summary Statistics for the before-the-Mid-1970s and 2012 Datasets in the Mid-Altitude Moist Sub-Area[a]

Periods	Before the mid-1970s (n=199[b])							
Cropping systems[c]	All plots (n=199)[1]	SCCS (n=96)[2]	CCCS (n=103)[3]		Pseudo-SCCS (n=7)[4]	*p*: [2] and [4][f]	*p*: [2] and [3]	*p*: [5] and [6]
Soil fertility management practices[d]		Only OFs 96 (100)	Only OFs 43 (42)[5]	No soil amendment 60 (58)[6]	No soil amendment 7			
Gender	0.90	0.91	0.79	0.98	0.86	*ns*	*ns*	***
Ethnic	0.08	0.08	0.02	0.12	0.00	*ns*	*ns*	*
Tenancy	0.08	0.33	0.44	0.23	0.14	*ns*	*ns*	**
Education	0.2±0.6	0.2±0.6	0.3±0.6	0.2±0.5	0.1±0.2	*ns*	*ns*	*ns*
Farm	3.1±1.6	3.1±1.6	3.3±1.5	2.9±1.6	2.3±0.9	*ns*	*ns*	*ns*
Labour	4.0±2.2	4.1±2.2	4.3±2.6	3.8±1.9	3.6±1.9	*ns*	*ns*	*ns*
Livestock	10.5±9.0	10.7±3.1	13.0±11.9	8.4±5.4	5.6±5.5	*ns*	*ns*	**
Donkey	2.1±1.2	2.2±1.2	2.3±1.4	1.9±1.0	1.4± 0.8	*ns*	*ns*	*
Fuel	2±7	1±5	2±7	2±10	11±30	*ns*	*ns*	*ns*
Plotsize	0.4±0.2	0.4±0.2	0.4±0.3	0.4±0.2	0.4± 0.1	*ns*	*ns*	*ns*
Distance	169±442	28±52	113±175	433±723	1189±337	***	***	***
0[e]	15 (8)	5 (5)	5 (12)	5 (8)	0 (0)			
0<≤100[e]	122 (61)	82 (85)	20 (46)	20 (33)	0 (0)			
100<≤1000[e]	54 (27)	9 (9)	18 (42)	27 (45)	0 (0)			
1000<[e]	8 (4)	0 (0)	0 (0)	8 (13)	7 (100)			

	In 2012 (n=282)							
	All plots (n=282)[7]	SCCS (n=140)[8]		CCCS (n=142)[9]		*p*: [8] and [9]	*p*: [10] and [11]	*p*: [12] and [13]	*p*: [1] and [7]
		Only OFs 124 (89)[10]	No soil amendment 16 (11)[11]	Only IFs 85 (60)[12]	OF and IFs 57 (40)[13]				
Gender	0.84	0.85	0.75	0.80	0.89	*ns*	*ns*	*ns*	***
Ethnic	0.12	0.10	0.19	0.16	0.07	*ns*	*ns*	*	***
Tenancy	No data	No data	No data	No data	No data				
Education	1.0±1.7	1.1±1.8	0.5±1.2	0.7±1.3	1.4±2.2	*ns*	*ns*	**	***
Farm	2.0±1.6	2.1±1.6	1.4±0.8	1.8±1.1	2.3±2.1	*ns*	*ns*	*	***
Labour	3.7±1.8	3.8±1.8	3.3±1.7	3.4±1.7	4.2±1.8	*ns*	*ns*	**	*ns*
Livestock	3.3±2.5	3.5±2.6	2.4±1.5	2.4±2.0	4.3±2.8	*ns*	*ns*	***	***
Donkey	1.3±1.0	1.3±1.0	1.1±0.9	1.1±0.8	1.5±1.2	*ns*	*ns*	**	***
Fuel	33±20	32±19	37±30	34±22	32±16	*ns*	*ns*	*ns*	***
Plotsize	0.2±0.1	0.2±0.2	0.2±0.1	0.3±0.1	0.3±0.1	***	*ns*	*ns*	***
Distance	437±712	27±80	1061±527	819±903	587±710	***	***	**	***
0[e]	74 (26)	67 (54)	0 (0)	5 (6)	2 (4)				
0<≤100[e]	72 (26)	47 (38)	1 (6)	13 (15)	12 (21)				
100<≤1000[e]	80 (28)	11 (9)	4 (25)	37 (44)	28 (49)				
1000<[e]	56 (20)	0 (0)	11 (69)	30 (35)	15 (26)				

Note: [a] Figures are means or mean±standard deviation.

[b] The total number of the plot data before the mid-1970s does not include pseudo-SCCS plots.

[c] SCCS; subsistence crop-based cropping system, CCCS; cash crop-based cropping system.

[d] OFs; organic fertilisers were applied, IFs; inorganic fertilisers were used. Numbers are frequency, and numbers in brackets are %.

[e] Segments of *distance* (m). Numbers are frequency, and numbers in brackets are %.

[f] e.g. "*p*: [2] and [4]" represents Pearson's chi-square tests or *t*-tests between [2] SCCS data before the mid-1970s and [4] pseudo-SCCS data. *ns*; not significant, * p<0.10, ** p<0.05, *** p<0.01.

plots in the before-the-mid-1970s dataset and 142 sample plots in the 2012 dataset (Table 6).

K-means cluster analysis (K=2) for the before-the-mid-1970s dataset did not show any consistency between the data categorised in Cluster 1 (196 data) and Cluster 2 (3 data) and the data categorised in the SCCS (96 data) and CCCS (103 data). Therefore, binomial logit analyses were performed for the pooled dataset.

K-means cluster analysis for the 2012 dataset found that the plot data categorised into Cluster 1 was the same as those in the SCCS subdataset. Those categorised into Cluster 2 were the same as those in the CCCS subdataset. Moreover, all the SCCS plots did not use IFs (*fer*=0), whereas all the CCCS plots used IFs (*fer*=1). Under these conditions, the bivariate probit models 3 and 4 were not formulated. The exogeneity tests showed contrasting results: The bivariate probit model 1 (the pooled dataset with *crop*) indicated the household heads considered their choices of OF and IF use independently (signs of atanh ρ and ρ were positive, suggesting a complementary relationship between OFs and IFs; however, the z-scores of atanh ρ indicated that H_0: ρ=0 were not rejected, and the likelihood ratio test also showed H_0: ρ=0 were not rejected). In contrast, the bivariate probit model 2 (the pooled dataset without *crop*) indicated that the two soil amendment choices were significant substitutes; those were the same results as Mukai [2023]. The bivariate probit analyses showed that the squared residual obtained from model 1 was 38.5 and that from model 2 was 97.3. The per cent correctly estimated values were 82% for model 1 and 60% for model 2. The BIC (Bayesian information criterion) was 368.2 for model 1 and 671.7 for model 2. These tests consistently showed that model 1 had a better goodness-of-fit than model 2. However, the bivariate probit analysis with model 1 did not show any meaningful results for farmers' IFs use. It was probably because of the collinearity between *fer* and *crop* (*fer* is always 0 when *crop*=0, whereas *fer* is always 1 when *crop*=1).

In these conditions, it can be better to analyse the 2012 pooled dataset using a model that does not consider a reciprocal relationship between OFs and IFs use because the household heads can consider the two soil amendment choices independently. The 2012 pooled dataset can also be analysed separately, representing the Cluster 1 subdataset (=SCCS subdataset) and Cluster 2 subdataset (=CCCS subdataset). Thus, four binomial logit models were formulated: (i) model 1 used the pooled dataset with the independent variable *crop* (shown as model C in Table 7), (ii) model 2 used the pooled dataset without *crop* (model D in Table 7), (iii) model 3 used the SCCS subdataset (model E in Table 7), and (iv) model 4 used the CCCS subdataset (model F in Table 7). Models 1, 3 and 4 assessed only the determinants of OFs application because of the collinearity between *fer* and *crop*. The bivariate probit analysis using model 2 (the pooled dataset without

Table 7. Binomial Logit (before the Mid-1970s and 2012) and Bivariate Probit (2012) Analyses[a]

Period	Before the mid-1970s[b]	2012						
Model	A Binomial logit (pooled)	B Bivariate probit (pooled) without *crop*		C Binomial logit (pooled) with *crop*	D Binomial logit (pooled) without *crop*		E Binomial logit (SCCS)	F Binomial logit (CCCS)
Dependent variables	OFs (*man*)	OFs (*man*)	IFs (*fer*)	OFs (*man*)	OFs (*man*)	IFs (*fer*)	OFs (*man*)	OFs (*man*)
Gender	-2.70**(1.29)	0.10 (0.25)	-0.03 (0.24)	0.18 (0.46)	0.19 (0.42)	-0.11 (0.41)	-0.27 (2.98)	0.14 (0.58)
Ethnic	-1.09* (0.65)	-0.41 (0.26)	0.11 (0.26)	-0.69 (0.50)	-0.63 (0.45)	0.12 (0.45)	1.26 (2.73)	-0.61 (0.67)
Education	0.04 (0.37)	0.12**(0.06)	0.01 (0.06)	0.26**(0.11)	0.20**(0.10)	0.02 (0.08)	1.30 (1.47)	0.25**(0.12)
Tenancy	0.65 (0.47)	Not used	Not used	Not used	Not used	Not used	Not used	Not used
Farm	0.02 (0.17)	0.05 (0.07)	0.01 (0.06)	0.10 (0.13)	0.08 (0.12)	0.01 (0.11)	0.03 (0.59)	0.06 (0.14)
Labour	-0.01 (0.11)	0.07 (0.06)	-0.02 (0.05)	0.14 (0.11)	0.13 (0.10)	-0.05 (0.09)	0.79 (0.94)	0.13 (0.12)
Livestock	0.09**(0.05)	0.10**(0.05)	0.01 (0.04)	0.20**(0.10)	0.19**(0.10)	0.01 (0.07)	0.13 (0.59)	0.24**(0.11)
Donkey	-0.09 (0.29)	0.03 (0.12)	-0.04 (0.10)	0.04 (0.22)	0.04 (0.21)	-0.04 (0.18)	-0.53 (1.43)	0.05 (0.24)
Crop	Omitted[c]	Not used	Not used	-2.10*** (0.37)	Not used	Not used	Not used	Not used
Plotsize	-0.77 (1.01)	-2.58***(0.70)	2.76***(0.64)	-2.94**(1.37)	-4.51***(1.20)	4.58***(1.10)	-17.50 (13.23)	-1.75 (1.66)
Distance	-0.01***(0.00)	-0.00***(0.00)	0.00***(0.00)	-0.00***(0.00)	-0.00***(0.00)	0.00***(0.00)	-0.02**(0.01)	-0.01** (0.00)
Sample no.	199		282	282	282	282	282	142
Wald χ^2	72.05***(10)		104.91***(18)	129.43***(10)	92.49***(9)	84.48***(10)	129.43***(10)	28.21***(9)
Log likelihood	-85.79		-276.59	-119.25	-137.72	-153.22	-119.25	-81.54
% correctly predicted (%)	79		60	82	79	72	82	73
Pseudo R^2	0.30		Not available	0.35	0.25	0.22	0.88	0.15
BIC	229.8		671.7	300.6	331.9	362.9	300.6	212.6

Note: [a] Figures are coefficients (standard errors). * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

[b] The analysis for the before-the-mid-1970s dataset did not include the pseudo-SCCS plot data.

[c] The variable *crop* was omitted from the binomial logit analysis for the before-the-mid-1970s dataset because of the collinearity between *man* and *crop* (*man* is always 1 when *crop*=0; Table 6).

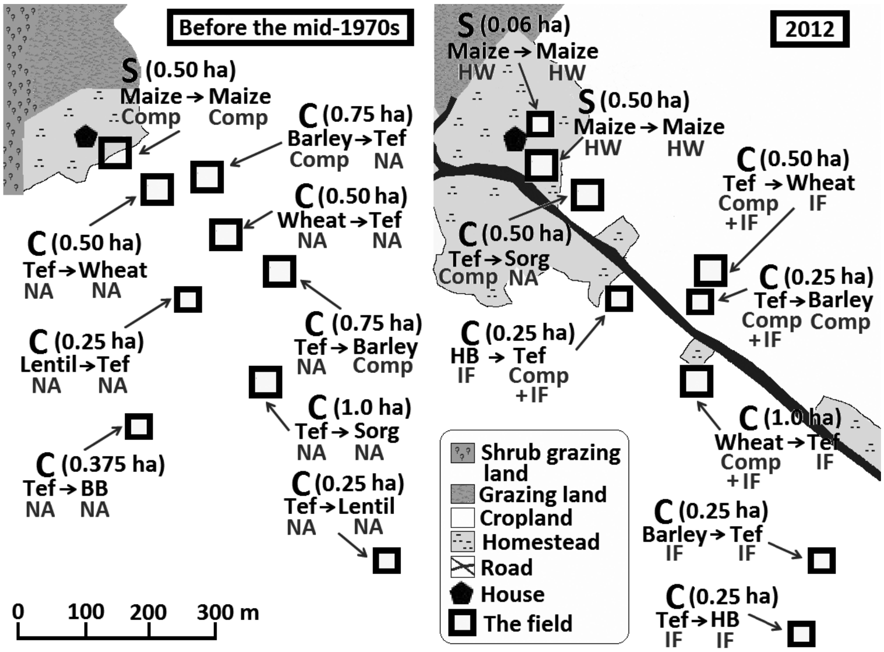

Fig. 4. Cropping Sequences and Soil Fertility Management Practices of Teshome Yadete (A Male Farmer Aged 68 at the Time of the Interview) in the Mid-Altitude Moist Sub-Area before the Mid-1970s (Left Figure) and 2012 (Right Figure)

Note: S and C denote SCCS and CCCS plots, respectively. Cropping sequences were described as the crop cultivated in the 1st year → that in the 2nd year (for the right figure, crop cultivated in 2011→ that in 2012). Sorg; sorghum, BB; broad beans, HB; haricot beans. Soil fertility management practices were represented in the third row. NA; no soil amendment, HW; household wastes application, Comp; compost application, IF; IFs use.

crop) was also shown (model B in Table 7).

Soil fertility management practices at the SCCS plots mostly stayed the same before the mid-1970s and 2012 (Table 6 and Fig. 4). Before the mid-1970s, OFs (compost or household wastes) were applied continuously to all the SCCS plots. In 2012, OFs were applied continuously to 89% of the SCCS plots, while 11% of the SCCS plots had no soil amendment practices (Table 6). All the SCCS plots that took no soil amendment option in 2012 were *ona* fields. *Onas* (the plural form of *ona*) were previous *aradas*, where soil fertility that a long-term OFs application had induced before remained somehow even after their latest homestead move.

Soil fertility management practices at the CCCS plots changed much from before the mid-1970s to 2012 (Table 6 and Fig. 4). Before the mid-1970s, 58% of the CCCS plots had no soil amendment practice, while OFs (compost or household wastes) were occasionally applied to the remaining 42% (Table 6). In 2012, 60% of the CCCS plots used only IFs, while, on the remaining 40%, IFs are regularly used and compost is occasionally applied. This change was probably because of a soil fertility decline in *masa* fields. *Masa* soils in both the mid-altitude moist and mid-altitude dry sub-areas have the mean available phosphorus (P) contents of 1.9–2.6 mg kg^{-1}. That is categorised as a very low Olsen P level for crop cultivation [Mukai 2019], while that in *aradas* was 10–11 mg kg^{-1}, categorised as a medium level. To obtain good yields from cash crops cultivated in *masa*, DAP application for supplementing P deficiency has recently become a must for farmers.

Before the mid-1970s, OFs were applied to all the 96 SCCS plots (Table 6). However, the determinants of OFs application to their maize fields are unclear in this situation. Therefore, additional plot data were collected from 7 household heads who had not had SCCS plots, i.e. who had not continuously cultivated maize on *aradas*, before the mid-1970s. These household heads were selected from those other than the before-the-mid-1970s dataset. The following questions were asked: (i) did they (or their parents) want to cultivate maize before the mid-1970s? If the answer was "yes," another additional question of "if you (your parents had) cultivated maize, what plot it would be (would have been)?" was asked, and then the attribute data of the corresponding plots and household head were collected. These additionally collected seven plots were referred to as pseudo-SCCS plots.7) *T*-tests or Pearson's chi-square tests were applied to detect differences in the means of the variables between the plot data of manured SCCS (n=96; "manured" referred to as any OFs were applied) and non-manured pseudo-SCCS (n=7; Table 6).

The binomial logit analyses for the before-the-mid-1970s dataset (model A in Table 7) indicated that the household heads who (i) were females (*gender*), (ii) owned a larger quantity of livestock (*livestock*), and (iii) had the plots that were closer to their houses (*distance*) significantly tended to apply OFs to their plots ($p<0.05$). The summary statistics showed that *distance* was the only variable that significantly differed between the manured SCCS plots and non-manured pseudo-SCCS plots (commuting distance; Table 6). All the household heads who did not hold any SCCS (pseudo-SCCS households) had commuting distances of over 1,000 m to their nearest fields. In contrast, 87% of the manured SCCS households had maize plots at a commuting distance of lesser than 100 m, with a 400-m distance as the maximum case. It was difficult for household heads with no field within approx. 400 m from their homesteads to apply OFs to their

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7) We can consider that the holders of these 7 plots preferred cultivating maize on the plot, but they gave up for a specific reason. These 7 pseudo-SCCS data were not used for the binomial logit analyses.

fields. Farmers apply as much as 6.3 Mg ha^{-1} of compost to their SCCS fields every 1.1 years [Mukai 2018], thus, giving up continuous maize cultivation. Summary statistics also showed that the household heads who (i) were females (*gender*), (ii) were landlords (*tenancy*), (iii) owned a larger quantity of livestock (*livestock*), and (iv) had plots with shorter commuting distances from their houses (*distance*) were significantly more likely to apply OFs to their CCCS plots before the mid-1970s (Table 6). A significant difference in variable *distance* between the options of no soil amendment and OFs application can be explained by the aforementioned nature of the OFs application techniques observed in the SCCS plots. Farmers divided the manured CCCS fields into some blocks and applied compost rotationally to each block once every several years. During the imperial era, many farmers cultivated crop fields as tenants. The odds ratio of the binomial logit analysis indicated that landlord households had a 3.2-fold higher probability of applying OFs than tenant households. Thus, the binomial logit analyses for the pooled dataset were consistent with the findings from the summary statistics.

The bivariate probit analysis for the 2012 dataset (model B in Table 7) demonstrated that the household heads who (i) spent long years in schools (*education*), (ii) own a larger quantity of livestock (*livestock*), (iii) had a smaller plot in size (*plotsize*), and (iv) had a short commuting distance plots (*distance*) were significantly more likely to apply OFs to their plots. The two binominal logit analyses for the pooled dataset (models C and D) also showed similar results to the bivariate probit analysis for the determinants of OFs application.[8] These results reflect the summary statistics for the 2012 pooled dataset (Table 4).

However, the two binomial logit analyses for the manured plots (models E and F in Table 7) showed contrasting results between the SCCS and CCCS subdatasets. The significant determinant was the only *distance* for the SCCS (model E), whereas those were (i) *education*, (ii) *livestock*, and (iii) *distance* for the CCCS (model F). Summary statistics showed that *distance*

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[8] The two binomial logit models for the pooled dataset with *crop* (model C) and without *crop* (model D) and two binomial logit models for the SCCS (model E) and CCCS (model F) subdatasets are compared in goodness-of-fit. The indicators used to assess it were (i) the squared residuals obtained from the pooled dataset (SSR$_1$ for model C and SSR$_2$ for model D) and the sum of the squared residuals obtained from the two subdatasets (SSR$_3$+SSR$_4$=SSR$_3$ for model E+SSR$_4$ for model F); (ii) the per cent correctly estimated values and (iii) the BIC [Mukai 2023]. For (i), SSR$_1$=38.2, SSR$_2$=43.8, SSR$_3$+SSR$_4$=29.1. For (ii), the per cent correctly estimated values=82% for model C, 79% for model D, 99% for model E, and 73% for model E. For (iii), the BIC=300.6 for model C, 331.9 for model D, 61.7 for model E, and 212.6 for model E. Thus, except model E showed a lower per cent correctly estimated value, other indicators demonstrated that the model with a dummy variable method (model C) showed better goodness-of-fit than the conventional model (model D). This agrees with the bivariate probit analyses and Mukai [2023]. Besides, the models with the data segmentation approach (models E and F) showed the best goodness-of-fit among the models compared. This was also the same finding as Mukai [2023].

was the only significant independent variable for the SCCS (*P*: [10] and [11] in Table 6). In contrast, the CCCS had several significant independent variables, such as *education*, *labour*, *livestock*, *donkey*, and *distance* ($p<0.05$; *P*: [12] and [13]), both of which generally support the binomial logit analyses with the two subdatasets (models E and F).

The bivariate probit and binomial logit analyses for the pooled dataset (models B, C, and D) appear to combine the two binomial logit analyses for the SCCS and CCCS subdatasets (models E and F). However, the analyses for the pooled dataset (models B, C, and D) and the summary statistics (Table 4) commonly showed (i) *plotsize* as a significant variable and (ii) the plots where IFs were used had a significantly longer commuting distance (*distance*). In contrast, the analyses with the two subdatasets (models E and F) and the summary statistics (Table 6) showed different results.

All the non-manured SCCS plots were in *ona* fields (previous SCCS plots in *aradas*) in 2012. Thus, it can be natural that neither differences in biophysical features, except *distance*, nor socioeconomic endowments of the household heads were observed between manured and non-manured plots. All the CCCS plots were situated in *masa* fields, where no difference in plot size was observed between manured plots (i.e. the plots that took the “OFs and IFs” option) and non-manured plots (i.e. the plots that took the “only IFs”) (*P*: [12] and [13] in Table 6). The important factor for farmers to successfully grow cash crops is employing all available soil amendment options (OFs and IFs). However, their practices depend on their resources endowments (e.g. *education*, *labour*, *livestock*, *donkey*) and the plot position (e.g. *distance*). In terms of commuting distances (*distance*) to the CCCS plots, considering the nature of compost application techniques observed over time, it is highly probable that farmers applied compost to the shorter commuting distance CCCS plots. Therefore, the binomial logit analyses and summary statistics for the SCCS and CCCS subdatasets (models E and F and [12] and [13] in Table 6) appear natural, representing field reality.

In the mid-altitude moist sub-area, the household heads did not use IFs at any SCCS plot and used IFs at all CCCS plots.9) The summary statistics and the econometric analyses for the pooled dataset most probably did not represent farmers’ determinants of IFs use. These represented the differences between the plots where IFs were used (the CCCS plots) and those where IFs were not used (the SCCS plots).

Summary statistics (Table 6) showed that female household heads significantly applied OFs to

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9) In another proximate way of putting it, the household heads did not use IFs for subsistence crops but used IFs for cash crops.

the CCCS plots before the mid-1970s.10) In contrast, female household heads became less likely to apply OFs to the SCCS and CCCS plots in 2012.11) When the distance to the manured CCCS plot was relatively short (113 m in the mean; Table 6) before the mid-1970s, female household heads had more advantages over male household heads in applying household wastes to the CCCS plot. However, in 2012, the mean distance to the manured CCCS plot increased to 587 m (Table 6). In addition, female household heads had significantly a lesser number of total family members and regular labour force (*labour*; 3.0 and 3.9 persons for the female and male, respectively), significantly lesser donkey and camel ownership levels (*donkey*; similarly, 1.0 and 1.3 heads), and significantly lesser livestock ownership level (*livestock*; 1.9 and 3.5 TLU) in 2012; these disadvantaged the female household heads to apply OFs to the CCCS plot. Of the 124 manured SCCS plots in 2012, 82 were situated at a distance shorter than 5 m from the household heads' houses, and the mean plot size (0.15 ha) was significantly smaller than that of the other 40 manured SCCS plots (0.31 ha). These are backyard maize plots, a new maize cultivation method in the early 1990s. Farmers established continuous maize cultivation fields of several hundred m^2 in their house-yards, where they dumped household wastes on the ground. These backyard maize plots decreased the plot size of the manured plots in the pooled dataset, which probably made *plotsize* a significant independent variable in the bivariate probit and binomial logit analyses with the pooled dataset (models B and D).

Thus, overall, the econometric analyses and the narrative inquiry interviews in the mid-altitude moist sub-area showed that the models with the data segmentation approach (models E and F) reflect the field reality. This was the same finding as Mukai [2023]. Second, the determinants of OFs application to the SCCS plots did not change much between the two periods. Over time, the available volume of animal dung and the commuting distance to the fields have been the major determinants of OFs application to the SCCS fields. Third, in contrast to the SCCS, farmers' determinants of OFs application to the CCCS plots appear to change much over the periods. *Tenancy* disappeared after the regime change; however, other resource endowments, such as *education*, *labour*, and *donkey*, were added.

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10) In Table 6, the mean *gender* value, 0.79 when the soil fertility management option was "only OFs" at the CCCS plots before the mid-1970s was significantly (p<0.01) lower than the value, 0.98 when the option was "no soil amendment" (*P*: [5] and [6]).

11) The mean *gender* value, 0.85, in the "only OFs" option was higher than that in the "no soil amendment," 0.75, for the SCCS. The mean *gender* value, 0.89, in the "OF and IFs" option was higher than that in the "Only IFs," 0.80, for the CCCS (both were insignificant).

3.2 *Changes in the Adoption Rate of Organic Fertiliser Techniques and Organic Fertiliser Application Areas in the Mid-Altitude Moist Sub-Area*

In the mid-altitude moist sub-area, the variable *distance* showed different pictures between the SCCS and CCCS plots over time (Table 8). The mean commuting distances in 2012 did not differ significantly from before the mid-1970s for the manured SCCS plots (from 28 m to 27 m; Table 8).[12] In contrast, the mean commuting distance to all the CCCS plots more than doubled from 300 m to 726 m between the two periods, and the mean distance to the manured CCCS plots increased by approximately six-fold (from 113 m to 587 m).

For the other key variables, consistent results were observed between the SCCS and CCCS for all the plots and manured plots (Table 8). Variable *labour* did not show any significant difference between the two periods. In contrast, the remaining variables, *farm*, *livestock*, *fuel* (percentage of cattle dung used for fuel), and *plotsize*, showed significant differences. The *livestock* and *donkey* (donkey and camel ownership) levels in 2012 were reduced to 30–40% and approx. 60% of those before the mid-1970s, respectively. The increase in *fuel* can partly help reduce the volume of animal dung applied to the plots.

Table 8. Comparisons of Several Key Variables before the Mid-1970s and 2012 in the Mid-Altitude Moist Sub-Area[a]

	SCCS subdataset						CCCS subdataset					
	All plots			Manured plots			All plots			Manured plots		
	1970s[b] (96)[c]	2012 (140)	*p*	1970s (96)	2012 (124)	*p*	1970s (103)	2012 (142)	*p*	1970s (43)	2012 (57)	*p*
Farm	3.1	2.0	**	3.1	2.1	**	3.0	2.0	**	3.3	2.3	*
Labour	4.1	3.7	*ns*	4.1	3.8	*ns*	4.0	3.7	*ns*	4.3	4.2	*ns*
Livestock	10.7	3.3	**	10.7	3.5	**	10.3	3.2	**	13.0	4.3	**
Donkey	2.2	1.3	**	2.2	1.3	**	2.1	1.3	**	2.3	1.5	**
Fuel	1	32	**	1	32	**	2	33	**	2	32	**
Plotsize	0.4	0.2	**	0.4	0.2	**	0.4	0.3	**	0.4	0.3	*
Distance	28	145	**	28	27	*ns*	300	726	**	113	587	**

Note: [a] Pearson's chi-square tests were applied to detect differences in the means of the variables between the two periods. *ns*; not significant, * $p<0.05$, ** $p<0.01$.

[b] 1970s; before the mid-1970s.

[c] Sample size.

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12) This might be because the commuting distance to the household waste application fields became shorter, from 31 m before the mid-1970s (n=37) to 8 m in 2012 (n=62; P=0.06), mainly because of the establishment of the backyard maize fields. Conversely, the distance to the compost application SCCS fields became longer, from 27 m before the mid-1970s (n=59) to 45 m in 2012 (n=62; not significant). Both offset each other, representing the phenomena for the SCCS plots.

How did these changes in the biophysical characteristics of the plots and the socioeconomic attributes of the household heads affect the soil fertility management practices? The proportions of the household heads who applied OFs (i.e., the adoption rate of the OF techniques) did not change much between the two periods, either for the SCCS or CCCS (Table 9). The total manured plot areas per household significantly declined to approximately half between the two periods for both the SCCS and CCCS. This probably was a response to the reduction in the total cropland size per household (*farm*) between the two periods (Table 8). The manured plot area per year per household also became nearly half for the SCCS, whereas it was almost identical for the CCCS. This may imply that the OFs application frequency to the SCCS plot stayed mostly the same between the two periods. In contrast, household heads applied OF more frequently to the CCCS fields in 2012 than before the mid-1970s. It was difficult to assess an accurate change in the OFs application dose between the two periods based on interviews with the household heads and a single-shot field measurement survey. However, because the rate of *livestock* reduction between the two periods was higher than the area reduction rate to which OFs were applied per year, the farmers might have coped with the decline in the available volume of animal dung by decreasing the application dose from the prior level.

3.3 *Oromo Indigenous Soil Fertility Management Practices in the Mid-Altitude Dry Sub-Area Before the Mid-1970s*

The target area (27.6 ha) was held by 18 and 19 Oromo household heads for the mid- and late-Imperial periods, respectively. All the informants interviewed said they had applied household wastes to some crop fields close to their houses (Fig. 5). They also said crop rotation had been a

Table 9. Changes in Organic Fertilisers Application before the Mid-1970s and 2012 in the Mid-Altitude Moist Sub-Area[a]

	SCCS subdataset			CCCS subdataset		
	Mid-1970s (n=96)	2012 (n=142)	p	Mid-1970s (n=103)	2012 (n=142)	p
No. of the household heads who applied OFs[b]	96 (100)	125 (88)	*ns*	43 (42)	58 (41)	*ns*
Total manured plot area per household (ha)[c]	0.4±0.2	0.2±0.2	**	1.1±1.4	0.6±0.4	**
Manured plot area per year per household (ha)[c]	0.4±0.2	0.2±0.2	**	0.4±0.5	0.4±0.2	*ns*

Note: [a] *ns*; not significant, * $p<0.05$, ** $p<0.01$.

[b] Figures are frequency, and figures in brackets are %. *T*-tests were applied to detect differences between the two periods.

[c] Mean±standard deviation. Pearson's chi-square tests were applied to detect differences between the two periods.

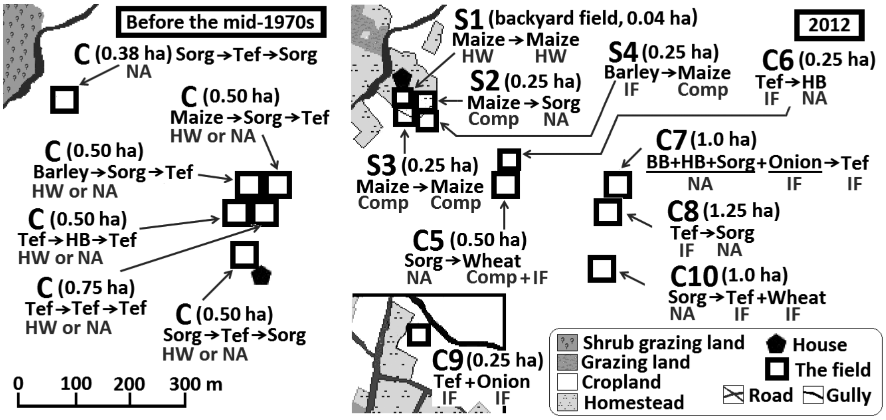

Fig. 5. Cropping Sequences and Soil Fertility Management Practices of Bedada Boru (A Male Farmer Aged 60 at the Time of the Interview) in the Mid-Altitude Dry Sub-Area before the Mid-1970s (Left Figure) and 2012 (Right Figure)

Note: Remarks are the same as those in Fig. 4. Cropping sequences before the mid-1970s are the crop cultivated in the 1st year → that in the 2nd year → that in the 3rd year. S1, S2, ---, C5, C6, --- correspond to the former house positions of Bedada Boru, indicated in Fig. 6. Before the mid-1970s, farmers regularly applied household wastes to a crop field or grazing land close to their homestead. However, those manured fields were usually not amended after their homestead moved to a different *masa*. That was why the soil fertility management practices in most fields before the mid-1970s were described as "HW or NA."

widespread practice.

Until the mid-1970s, the Oromo in the study area frequently changed their homestead positions (Fig. 6). Whenever they moved, they established a new house on a relatively unfertile field (*masa*), and grazing land (referred to as *thithisa*) was placed in an immediate downslope area from their house. Farmers piled up household wastes at a specific place in their house-yards and sometimes scattered them on their house-yards and grazing land. They applied 4–5 Mg ha^{-1} of household wastes to their vicinity every year. When a kraal in their house-yard became too wet during the rainy season, they built a simple kraal on their grazing land and moved their livestock there. All the informants also said that farmers had intentionally shifted the position of this temporary kraal year by year. Using these methods of applying household wastes and livestock excrement over several to over ten years, a former unfertile field (*masa*) gained soil fertility and became fertile (*arada*). Farmers then moved to the next unfertile field (*masa*) to boost the soil fertility of that field. Whenever a homestead transfer was performed, a group of paternal relatives moved together (Fig. 6).

These homestead transfers were performed basically from a downslope to an upslope direction

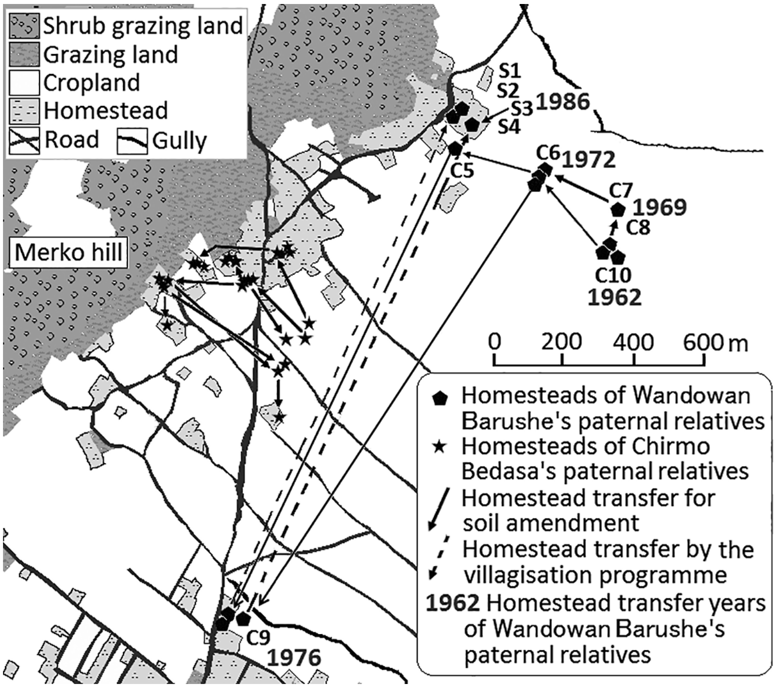

Fig. 6. Two Examples of Homestead Transfers of the Oromo Paternal Relatives Headed by Wandowan Barushe and Chirmo Bedasa

Note: S1, S2, ---, C5, C6, and C10 correspond to those shown in Fig. 4. The homestead transfers and transferred years were described for Wandowan Barushe's paternal relatives. Wandowan Barushe was Bedada Boru's paternal grandfather. Land use/cover was the state in 2012.

(Fig. 6). Farmers first amended the fields situated around the boundary between the gentle-slope cropland (Fig. 3) and gentle-slope homestead and finally settled at areas around the boundary between the gentle-slope homestead and steep-slope grazing lands. Most of the steep-slope grazing land area was rock outcropping land. By settling in the unfavourable lands for crop cultivation, they attempted to maximise the land productivity of the other arable cropland. To perform this practice, the homestead composition of the Oromo observed until the mid-1970s was simple. Their homesteads comprised only a house, granary, and kraal. Because their homesteads were structured on the presumption that they would move shortly, they were advised not to surround the homestead with stone fences or plant tree seedlings in their house-yards.

3.4 *Changes in Soil Fertility Management Practices in the Mid-Altitude Dry Sub-Area after the Mid-1970s*

After the mid-1970s, the Oromo indigenous cropping systems/sequences and soil fertility management practices changed markedly. Their indigenous soil fertility management practices, i.e. turning unfertile *masas* into fertile *aradas* by changing their homesteads, ended. This was because: first, farmers had moved towards the rock outcropping land. Currently, most homesteads are situated between the gentle-slope homestead and steep-slope grazing land areas (Fig. 6). Second, because the population increased and land tenure relations around the gentle-slope homestead area became complicated, the space and scope for individual households to change their homestead positions became scarcer. Third, the indigenous practice of establishing the grazing land immediately downslope from a homestead ended. This occurred primarily when the homesteads and grazing land areas diminished and became too narrow to place new grazing land. In the 27.6 ha target area, the mean homesteads and grazing lands held by a household significantly reduced from 0.80±0.27 ha in 1957 and 1972 to 0.12±0.06 ha in 2005 ($p<0.01$; Pearson's chi-square test). Fourth, the Derg regime implemented the villagisation programme in 1986 in the Boset district [Geda 2018] (Fig. 6). The land policy of the socialist Derg regime, agglomerated rural settlement, affected the Oromo indigenous soil fertility management practices. Around this period, the Oromo began surrounding their homesteads with hedges (primarily *Euphorbia leucodendron*) and stone fences. Seedling plantations within their homesteads became a popular practice. Thus, their homestead structure and composition changed from those aimed at a future move to a long-term settlement, similar to the Amhara.

The cropping sequences and soil fertility management practices observed in 2012 in the mid-altitude dry sub-area (Fig. 5) are: first. The Oromo farmers began compost and household wastes applications to turn unfertile fields (*masas*) into fertile fields (*aradas*), where they continuously cultivated maize, i.e. SCCS maize fields. Second, farmers continued the rotational cropping of cash crops and subsistence crops other than maize in *masas*, where IFs are used whenever cash crops are cultivated, and compost is occasionally applied rotationally, i.e. CCCS fields. Thus, after the Oromo in the mid-altitude dry sub-area lost their indigenous soil fertility management practices, the new soil fertility management practices that the Oromo adopted were what the Amhara had established in the mid-altitude moist sub-area.

3.5 *Resource Constraints and Integrated Soil Fertility Management*

In the mid-altitude moist sub-area, most household heads (100% of the sample household heads before the mid-1970s and 89% in 2012) held continuously cultivated maize-SCCS fields in *aradas*. Between the two periods, the proportions of manured plots did not change much for both SCCS (89–100%) and CCCS (approx. 40%; Table 6). The adoption rate of the OF techniques did not change much over time. Soil fertility decline in *masa* fields and the introduction of IF techniques were the primary drivers for farmers in the mid-altitude moist sub-area to change their soil fertility management practices in the CCCS field. In the CCCS field, IFs are used whenever cash crops are cultivated, and compost was applied to 40% of the plots in 2012 (Table 6). The bivariate probit analysis with the variable *crop* for the 2012 pooled dataset found that farmers' choice of the OFs and IFs use was independent, at least, not substitutability. In the mid-altitude dry sub-area, the cropping systems and soil fertility management practices taken by the Oromo after the mid-1970s have become similar to those established by the Amhara in the mid-altitude moist sub-area. All the evidence supports that the soil fertility management practices observed in the study area follow the concept of integrated soil fertility management, the combined use of OFs and IFs. Thus, for sustainable agricultural intensification in the northern semi-arid Ethiopian Rift Valley, how to intensify the present continuous trend in the future should be considered.

In the mid-altitude moist sub-area, the available volume of animal dung and the commuting distance to the plots have been the major determinants of OFs application to both the SCCS and CCCS plots over time. These determinants align with the nine recent technology adoption studies (Table 1) and Mukai [2023] from the northern semi-arid Ethiopian Rift Valley. Of the nine studies, (i) all studies found livestock ownership levels positively affected OFs application, and seven found the relationship was significant ($p<0.1$). (ii) eight studies took a commuting distance to the sample plots as a dependent variable, of which seven studies found commuting distance negatively affected OFs application, and four found the relationship was significant ($p<0.1$). These two factors also are likely to affect IF use (Table 1). Greater livestock ownership is associated with greater use of seeds and IFs, probably because the income generated from cattle products helps farmers afford to buy these inputs [Pender and Gebremedhin 2006]. In association with a generational change, new households were transferred lands in relatively distant places or distributed unfavourably located fields from their parents or peasant associations in their villages. That was quantitatively proven in Southern Ethiopia [Bezu and Holden 2014], one of the densely populated areas in Ethiopia. The mean household farm size was 0.86 ha [Bezu and Holden 2014], much smaller than that in the mid-altitude moist sub-area, 2.0 ha (Table 7). Based on the household survey data collected from 93 Highland districts of Ethiopia (densely populated areas), Headey *et al.* [2014] found that the mean household farm size (0.96 ha), which is very small by international standards, is declining over time. He also found that young rural households particularly faced severe land constraints. Thus, land fragmentation and the increasing commuting distance to the SCCS and CCCS fields caused by population increase are critical constraints in determining farmers' soil fertility management strategies in the study area and densely populated areas in Ethiopia.

The second point Headey *et al.* [2014] found was that land-constrained farmers use significantly more purchased input costs per hectare, such as IFs and improved seeds. This agrees with Pender and Gebremedhin [2006] from the semi-arid highlands, Tigray, and partly agrees with Benin [2006] from the sub-humid highlands, Amhara, and Josephson *et al.* [2014] with 1,293 household data (Ethiopian rural household surveys) collected from diversified farming systems in the country. Furthermore, these agree with the primary drivers of a recent rapid increase in the nationwide maize productivity [Abate *et al.* 2015] and other cereals, such as tef, wheat, and barley [Bachewe *et al.* 2018]. Josephson *et al.* [2014] found that the intensity of IF use increases as rural population density rises until around 2.0 persons ha^{-1} in Ethiopia. These findings agree with the recent trend of IFs use in the study area. IFs were used for all the CCCS plots whenever cash crops were cultivated. Mukai [2023] also found this finding in the northern semi-arid Ethiopian Rift Valley.

The third point found by Headey *et al.* [2014] was that land-constrained farmers use more family labour and, therefore, achieve higher maize and tef yields and higher gross income per hectare. However, Pender and Gebremedhin [2006], Benin [2006], and Josephson *et al.* [2014] found that higher population density was not associated with an increase in crop yields. Population pressure is associated with more intensive use of labour, improved seeds, and IFs, the findings of which are consistent with the predictions of population-induced intensification, as hypothesised by Boserup [1965] and her followers [Pender and Gebremedhin 2006]. These agree with the findings obtained from the qualitative and quantitative analyses for the OFs application to the CCCS plots in the mid-altitude moist sub-area. Recently, the household heads' resources endowments, such as *education*, *labour*, and *donkey*, have become the major determinants of OFs application to the cash crops at the CCCS plots.

3.6 *Integrated Soil Fertility Management toward Agricultural Intensification*

Nin-Pratt [2015] divided SSA countries into four groups in terms of population density: G1 (the mean population density of 0.12 person ha^{-1}), G2 (0.30 person ha^{-1}), G3 (0.54 person ha^{-1}), and G4 (1.85 person ha^{-1}). He found that sparsely populated countries, such as G1 and G2, increased output following a land-abundant path that included (*a*) more land incorporated into crop production and (*b*) increased cropping intensity through reducing fallow periods. In contrast, in the countries with over 0.5 person ha^{-1}, i.e. G3 and G4, the contribution of the (*c*) yield increase substantially gained. Within G1, G2, and G3 countries, high IF use levels were related to the above (*a*) but not to (*c*). In contrast, in the case of G4 countries, IF use was not correlated with (*a*), but high IF use levels were expected with higher (*c*). Nin-Pratt [2015] further suggested that his hypotheses could be more applicable to highland temperate and maize-mixed systems in Eastern and Southern Africa.

Population densities of Boset district were 0.39 in the mid-1970s, 0.57 in 1984, and 1.02 person ha^{-1} in 2012 (estimated by CSA [1984–2017]). In the 1957 aerial photographs, roughly half of the cultivated fields in the Tebo-Geldia catchments in 2012 had not been exploited yet. Considering the population density of the catchments area in 1957, the catchments were positioned in G1 or G2 since the pioneer migrants had begun forest exploitation. The area surely had a land-abundant path similar to the G1 and G2 countries at the time. The 1972 aerial photographs showed that most cultivated fields in 2012 had already become croplands. Since then, the phase of agricultural intensification in the catchments changed to yield-increase- and commercialisation-oriented ones with integrated soil fertility management practices. This agricultural intensification process appears to agree with the one typically seen in G3 countries. Thus, the historical agricultural intensification processes observed in the study area support the hypotheses suggested by Nin-Pratt [2015]. These findings suggest that the unfavourable continuous resource constraints in the northern semi-arid Ethiopian Rift Valley do not necessarily hinder future agricultural intensification. Farmers have recently become more interested in investing limited organic resources into cash crop cultivation. The future resource constraints probably encourage farmers to use more purchased costs per hectare for IFs and improved seeds in the due intensification course from G3 to G4.

Thus, to maintain the present trend of integrated soil fertility management practices in the study area, encouraging OFs use under aggravating conditions is critical. Since the beginning of the 2000s, the district agriculture office began giving fast compost training to farmers [Mukai and Oyanagi 2019]. The district agriculture office has planned this training, technically instructed by Melkassa agricultural research centre (a regional agricultural research institute) and financially supported by World Vision (an international NGO). Mukai [2023] surveyed two neighbouring districts, Adama and Boset. He found that: (i) approximately one-third of compost application farmers to their CCCS plots replied either “I acquired the compost techniques by fast compost training” or “I knew it previously, but the training facilitated its use.” Moreover, (ii) the training could help significantly more farmers practice the combined use of compost and IFs on their CCCS plots. The indigenous compost (*kosi*) and introduced compost (fast compost) contain approximately one-third of animal dung and the remaining two-thirds of other organic materials in volume (maize and sorghum stalks, crop residue, feed refusals, kitchen ash) collected from their house-yards and fields. It effectively utilises locally available organic materials besides livestock dung. Mukai and Oyanagi [2019] found that because *kosi* and fast compost released a limited amount of nitrogen in the soil in an application year, both compost showed low substitutability for IFs as quick-acting fertilisers. Instead, they cultivate the soil in their medium- or long-term application and gain crop yields by increasing total carbon and nitrogen in the manured soil; thus, OFs application and IFs use can be supplementary soil fertility management practices. Compost preparation and application techniques is a countermeasure against the increasingly unavailable volume of animal dung and a good example of strengthening linkages between research, extension services, and farmers, one of the requirements for sustainable soil fertility management in SSA [Stewart *et al.* 2020].13)

4. Conclusions

Since the 1870s, the Oromo repeated short-distance transfers to amend the field soil. Because of land constraints and the enforcement of the villagisation policy, they began a sedentary life similar to the Amhara. Currently, the cropping systems taken by both Amhara and Oromo can be categorised into subsistence-crop-based and cash-crop-based ones. After the soil fertility decline in *masa* fields and the introduction of the IF techniques, their soil amendment strategies have been characterised as integrated soil fertility management. Despite the continuous deterioration in the limited availability of animal dung and increasing commuting distances to the fields, primary determinants of OFs application, the adoption rate of the OF techniques and the proportion of manured fields have not changed much over time in the northern semi-arid Ethiopian Rift Valley. Farmers have recently been more inclined to invest limited organic resources in cash crop cultivation by partly sacrificing their share for subsistence-based crops. These historical paths of the agricultural intensification in the northern semi-arid Ethiopian Rift Valley support the hypothesis of population-induced agricultural intensification deduced from

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13) Stewart *et al.* [2020] conducted questionnaire surveys and summit meetings in 2017. The questionnaire surveys collected their opinions from 491 multi-disciplinary actors working in SSA soil fertility, including international agricultural centres, national agricultural research and extension systems, agronomic/soil researchers, extension and development agencies, the private sector, social scientists, and farmer organisations in 32 SSA countries. They provided evidence-based recommendations that local research institutes conduct quality soil testing, establish regionally specific fertiliser response recommendations, and recommend improved/updated cropping systems to farmers through strengthened linkages between research, extension services, and farmers. Increasing access to and use of quality organic materials was consistently identified and prioritised by all regions for the goal of improving soil fertility.

spatial and temporal evidence in SSA. Part of Eastern and Southern Africa and West Africa Sahelian countries, where the crop-livestock system prevails, the future resource constraints can be counteracted by more intensified soil fertility management strategies of OF-IF integration. How to effectively utilise available organic resources in farmers' vicinity should be considered in linkages between research, extension services, and farmers to maintain sustainable soil fertility management in the local contexts.

Acknowledgements

This study was financially supported by the Ministry of Agriculture, Forestry and Fisheries, Japan. The author would like to thank Merko Odalega and Koka Gifawasen villagers for cooperating with this study.

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