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Ethiopian agriculture has greater potential for carbon sequestration than previously estimated

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Abstract

More than half of the cultivation-induced carbon loss from agricultural soils could be restored through improved management. To incentivise carbon sequestration, the potential of improved practices needs to be verified. To date, there is sparse empirical evidence of carbon sequestration through improved practices in East-Africa. Here, we show that agroforestry and restrained grazing had a greater stock of soil carbon than their bordering pair-matched controls, but the difference was less obvious with terracing. The controls were treeless cultivated fields for agroforestry, on slopes not terraced for terracing, and permanent pasture for restrained grazing, representing traditionally managed agricultural practices dominant in the case regions. The gain by the improved management depended on the carbon stocks in the control plots. Agroforestry for 6–20 years led to 11.4 Mg ha^{-1} and restrained grazing for 6–17 years to 9.6 Mg ha^{-1} greater median soil carbon stock compared with the traditional management. The empirical estimates are higher than previous process-model-based estimates and indicate that Ethiopian agriculture has greater potential to sequester carbon in soil than previously estimated.

Keywords: agricultural practices, carbon stock, climate change, East-Africa, mitigation, soil

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Introduction

Converting forests to agricultural land together with unsustainable land use has caused soil erosion and depletion of soil carbon stock in large areas in East-Africa (Lal, 2004; Smith *et al*., 2007). Use of manure and crop residues for energy has reduced carbon inputs ending up to soil (Rimhanen & Kahiluoto, 2014) and free grazing has declined vegetation cover and exposed soil to erosive rains (Nyssen *et al*., 2005). For example in Ethiopia, agricultural soils have lost about 230–670 Mt of carbon since 1950s (Girmay *et al*., 2008). Since the end of the 19th century the government of Ethiopia has implemented regreening projects in order to restore degraded soils (Lemenih & Kassa, 2014). Practices include restricting grazing, building terraces and establishment of agroforestry (Hadgu *et al*., 2009; Tefera & Sterk, 2010; Lemenih & Kassa, 2014). At the New York Climate Summit 2014 Ethiopia engaged to restore further 15 million hectares of degraded land by 2030 (UN 2014). This equals 15% of the total land area of Ethiopia. The large area of severely degraded agricultural land, the low costs of improved management practices and the benefits for soil productivity (Schmidt *et al*., 2011) make carbon sequestration through improved agricultural management a worthwhile option to both mitigate and adapt to climate change (Smith & Olesen, 2010; Kahiluoto *et al*., 2014) in East Africa. Agricultural soils can, under favorable conditions, conserve even more carbon than soils with natural vegetation (Six *et al*., 2002) and have twice the potential for carbon sequestration relative to the aboveground biomass (Tschakert, 2004; Takimoto *et al*., 2008). The technical mitigation potential of African agricultural sector corresponds to 17% of the global total mitigation potential by the year 2030, most of the potential representing carbon sequestration in cropland and grazing land (Smith *et al*., 2008).

The lack of empirical estimates of soil carbon sequestration potential of agricultural practices has been argued to be one of the major bottlenecks preventing the introduction of carbon payments to African farmers (Bryan *et al*., 2010; Kahiluoto *et al*., 2012, 2014). Previous studies from Ethiopia have explored carbon stocks of different land uses (Solomon *et al*., 2002; Lemenih & Itanna, 2004; Lemma *et al*., 2006; Gelaw *et al*., 2014), especially changes in carbon stocks after the transition from forest to agriculture (Solomon *et al*., 2002; Lemenih & Itanna, 2004) and after establishment of exotic tree monoculture plantations on agricultural land (Lemma *et al*., 2006). The published estimates of carbon

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sequestration potential of agricultural practices are based on process models or serve model parameterization (Farage *et al.*, 2007; Kamoni *et al.*, 2007; Smith *et al.*, 2008; Batjes, 2014). Consequently, empirical knowledge of agricultural carbon sequestration in East-Africa is needed.

The aim of this study was to empirically quantify the soil carbon sequestration potential under 'improved management' in comparison with traditional farming. Three improved management practices with the longest histories in the study regions, agroforestry, restrained grazing, and farmland terracing, were each compared with adjacent controls of corresponding traditional farming dominant in the case regions. We hypothesized that the improved management practices increase soil carbon stock compared to traditional farming as a result of increased carbon inputs and reduced soil disturbance. Furthermore, explanatory factors for the carbon sequestration potential are discussed.

Materials and methods

Description of the study areas

The study was conducted in Kobo, Amhara region, and in Sire, Oromia region, which represent the major food-producing areas of Ethiopia and exhibit a range of agroecological and socioeconomic features (Fig. 1). The mean annual temperature is 21–25 °C in Kobo and 15–20 °C in Sire. Most of the rain falls in August and July (Fig. 2).

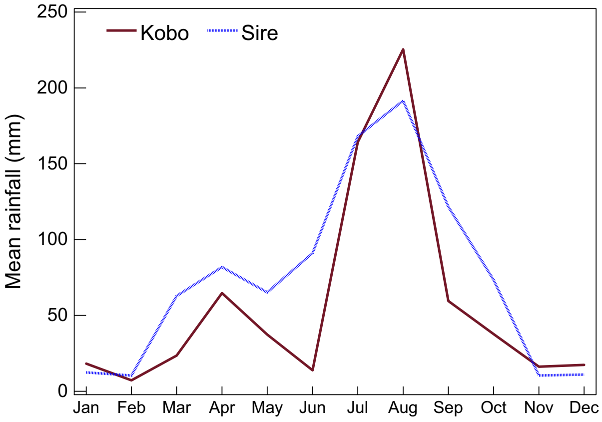

Fig. 2 Monthly mean rainfall in Kobo and Sire in the years 1996–2010 (excluding year 2001 due to incomplete data).

In Kobo, severe soil erosion due to deforestation, overgrazing, and the cultivation of steep slopes results in low agricultural productivity. In Sire, the landscape is mainly flat with gentle slopes. The soils are relatively fertile with a medium soil-degradation rate, resulting in higher yields, and holding sizes are larger, enabling more diverse crop rotations than

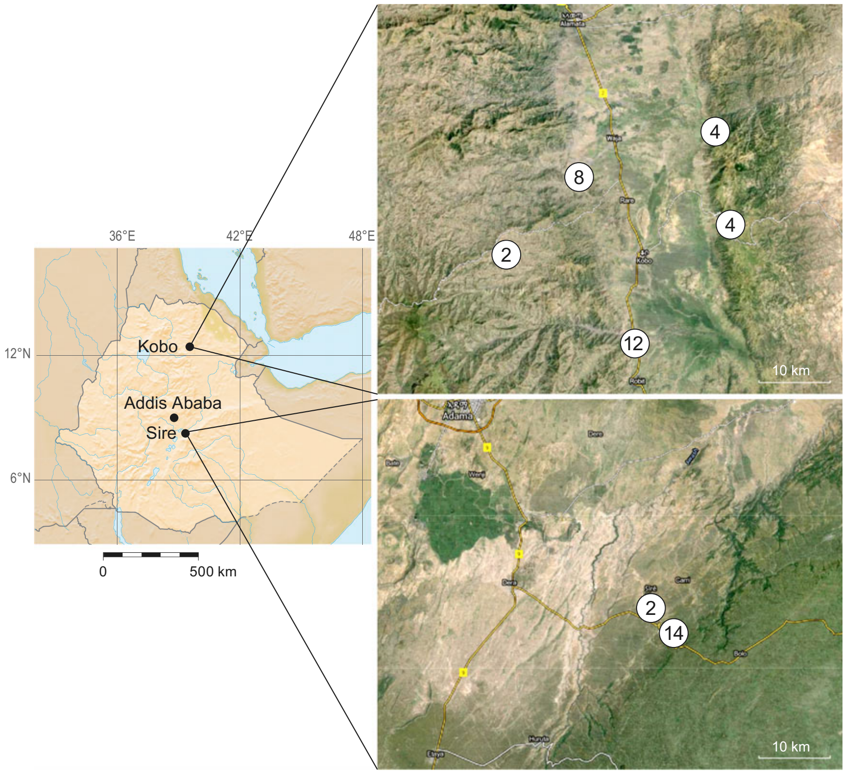

Fig. 1 Locations of the study regions Kobo and Sire and the study plots within the regions. The plot locations are marked with white circles, with the figure within each circle referring to the number of study plots within the location (Google Maps 2016).

in Kobo. In both study regions agriculture is characterized by 'highland temperate mixed farming' according to FAO's farming system typology (Dixon *et al*., 2001). That farming system occupies approximately one-third of the land area in Ethiopia. Average farm size is 1–2 ha. In Kobo the most common cultivated plants are great millet (*Sorghum bicolor* L.), wheat (*Triticum* spp. L.), teff (*Eragrostis tef* (*Zucc.*)*Trotter*) and barley (*Hordeum vulgare* L.). In Sire crop rotations are more diverse containing teff, wheat, barley, maize (*Zea mays* L.), vegetables, and pulses. The number of livestock is high. The main sources of income are from the sale of animals and animal products, local beer and crops (Dixon *et al*., 2001). Agriculture is rainfed, characterized by low inputs and low outputs. Lack of firewood has resulted in the use of cow dung as fuel and reduced its use as fertilizer (Rimhanen & Kahiluoto, 2014). Fields are cleared after harvesting from crop residues for fodder and fuel.

Compared management practices

Assessment of the carbon sequestration potential of improved agricultural practices was based on comparing three existing and contrasting practices, i.e., agroforestry, areas with restrained grazing and farmland terracing, with corresponding traditional farming practices which preceded the improved practices and still prevailed in the area. The improved practices were adopted decades ago to improve agricultural productivity. They varied in the study regions due to the agroecological and socioeconomic conditions, such as available water resources, topography, and collaborative traditions. In areas of restrained grazing the vegetation was mainly *Acacia* species (e.g., *A. abyssinia*, *A. seyal*, *A. tortilis*) (Table 1). The agroforestry plots were of the multistrata, home-garden type (Young, 1997). Controls for terracing and agroforestry were treeless rain-fed cultivated (arable) fields without terraces and trees, and for areas with restrained grazing uncultivated, freely grazed land. In the traditional and terraced farmlands, the cropping was practised without fallow periods. After harvesting, crop residues were removed and free grazing was allowed. Soil carbon concentration varied between 0.9% and 3.2% for agroforestry land and its control, 0.7% and 2.8% for areas of restrained grazing and its control and 0.3% and 3.6% for terracing and its control. The median management duration was 8.5 years for agroforestry, 13 years for restrained grazing, and 7 years for terracing.

Sampling design

The soil samples were collected in October–November 2010 using a matched pairs design (Koopmans, 1981). Soil was sampled from 23 plot pairs, each pair including a plot for an improved management practice and a traditionally managed control plot which was adjacent and bordering to the improved plot. Apart from differences due to management history, the plots close together in a field can be expected to be alike. The improved management practice was restrained grazing in seven of the plot pairs, terracing in eight plot pairs and agroforestry in eight plot pairs. Terracing and restrained grazing were sampled in Kobo and agroforestry around homesteads in Sire. The management history of the plots was confirmed by interviewing farmers. The accessible plot pairs were identified in a haphazard manner. From the identified plots of the improved management practices those plots were selected that had been under the management for the longest time. Besides proximity of the plots of the improved and traditional management practices, the criteria for pairing the plots were the same management history before conversion to improved management and the visual assessment of similar topography, soil type, and texture. The similarity of the plots of the improved managements to their traditional controls was also confirmed regarding altitude, slope, and soil texture (Table 2). Each plot was divided into three subplots to explore the within-plot variation. For each subplot, ten subsamples from the 0–15 cm soil layer were taken with an auger and pooled for soil analyses. Two bulk density samples were taken from each subplot at the same depth as the augered soil samples with a core sampler volume of 104 cm^3 in Kobo and 98 cm^3 in Sire. Means of the measurements from the three subplots were used as observations in the statistical analyses.

Soil analyses

The soil samples were air dried and ground (<2 mm). The total carbon concentrations were analysed by dry combustion at 1100 °C using the Leco CN-2000 analyser (Leco Corporation, St. Joseph, MI, USA). This analysis was performed for original samples and those treated with 6 M HCl to remove carbonate carbon (0–0.55%, median 0.10%). The results presented in this paper represent carbon contained in organic matter, remaining in the soil after the HCl treatment. The bulk density samples were dried at 105 °C for 12 hours and weighed. The bulk density (ρ_b) (g cm^{-3}) was calculated as the dry weight of the soil divided by the volume of the soil. Carbon stocks (Mg ha^{-1}) were primarily calculated by multiplying the concentrations (%) of soil carbon by the bulk density (g cm^{-3}) and the depth of the sampled soil (15 cm) and also expressed in kg per 1 Mg of soil.

Statistical analyses

The design was a split-plot type in which the three groups of plot pairs (agroforestry, areas of restrained grazing and terracing) were the levels of the whole-plot factor and the two management practices (traditional and improved) were the levels of the subplot factor (Fig. 3). Consequently, the statistical analysis of soil carbon stock was based on a mixed model for a split-plot design including three fixed effects (main effects of the whole-plot factor and the subplot factor and their interaction) and two random effects (whole-plot error and subplot error). The carbon stocks of the plots within each plot pair were positively correlated. This was taken into account in the model with the compound symmetry covariance structure (Gbur *et al*., 2012) which was estimated separately for the three improved management practices. To satisfy the distribu-

Table 1 Plant species composition in the study plots

Management practice	Plot							
	1	2	3	4	5	6	7	8
(a) Agroforestry	*Acacia* Mill. spp. *Carica papaya* L. *Coffea arabica* L. *Ensete ventricosum Welw. Cheeseman* *Mangifera indica* L. *Persea americana* L.	*Carica papaya* L. *Citrus sinensis* L. *Citrus limon* L. *Mangifera indica* L. *Musa acuminata* Colla *Saccharum officinarum* L. *Solanum lycopersicum* L. *Zea mays* L.	*Acacia* Mill. spp. *Coffea arabica* L. *Mangifera indica* L. *Musa acuminata* Colla *Sesbania sesban* (L.) Merr. *Phaseolus vulgaris* L. *Zea mays* L.	*Capsicum annuum* L. *Carica papaya* L. *Coffea arabica* L. *Citrus limon* L. *Mangifera indica* L. *Musa acuminata* Colla *Persea americana* L. *Solanum lycopersicum* L. *Solanum tuberosum* L.	*Brassica oleracea* L. *Catha edulis* Forsk. *Citrus limon* L. *Coffea arabica* L. *Ensete ventricosum* (Welw.) Cheeseman *Jatropha curcas* L. *Mangifera indica* L. *Musa acuminata* Colla *Pennisetum purpureum* Schumach.	*Acacia* Mill. spp. *Catha edulis* Forsk. *Carica papaya* L. *Capsicum annuum* L. *Coffea arabica* L. Eucalyptus globulus Labill. *Jatropha curcas* L. *Sesbania sesban* (L.) Merr. *Solanum lycopersicum* L. *Punica granatum* L. *Solanum lycopersicum* L. *Zea mays* L.	*Acacia* Mill. spp. *Coffea arabica* L. *Ensete ventricosum* (Welw.) Cheeseman Eucalyptus globulus Labill *Mangifera indica* L. *Musa acuminata* Colla *Persea americana* L. *Saccharum officinarum* L.	*Acacia* Mill. spp. *Coffea arabica* L. *Juniperus procera* L. *Mangifera indica* L. *Olea Africana* Mill. *Persea americana* L. *Phaseolus vulgaris* L. *Zea mays* L.
Control	*Zea mays* L.	*Zea mays* L.	*Phaseolus vulgaris* L. *Zea mays* L.	*Triticum* spp. L.	*Phaseolus vulgaris* L. *Triticum* spp. L.	*Zea mays* L.	*Allium cepa* L. *Eragrostis tef* (Zucc.) Trotter *Triticum* spp. L.	*Phaseolus vulgaris* L. *Zea mays* L.
(b) Restrained grazing	*Acacia Abyssinia* Hochst. ex Benth.	*Acacia seyal* Del.	*Acacia tortilis* (Forssk.) Hayne	*Acacia tortilis* (Forssk.) Hayne *Acacia Nilotica* (L.) Willd. ex Del. *Acacia seyal* Del.	*Acacia tortilis* (Forssk.) Hayne *Acacia Nilotica* (L.) Willd. ex Del. *Acacia seyal* Del.	*Acacia tortilis* (Forssk.) Hayne *Acacia Nilotica* (L.) Willd. ex Del. *Acacia seyal* Del.	*Acacia tortilis* (Forssk.) Hayne *Acacia Nilotica* (L.) Willd. ex Del. *Acacia seyal* Del.	
Control	Bushes	Bushes	Bushes	Bushes	Bushes	Bushes	Bushes	
(c) Terracing	*Hordeum vulgare* L. *Lens culinaris* L. *Triticum* spp. L.	*Eragrostis tef* (Zucc.) Trotter *Hordeum vulgare* L. *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.
Control	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.	*Eragrostis tef* (Zucc.) Trotter *Sorghum bicolor* L.

tional assumptions of the model carbon stocks were log-transformed. Carbon concentration (values between 0 and 1) was analyzed as a Beta-distributed variable according to the corresponding generalized linear mixed model for a split-plot design with the logit link function (Gbur *et al.*, 2012). The model was fitted using the pseudo likelihood estimation method (Gbur *et al.*, 2012). Analysis of covariance was used to compare the impact of the improved management practices on soil carbon stock and to eliminate the differences in the durations of the improved practices and in the carbon stocks of the adjacent traditional plots. The data of terracing included one plot pair in which carbon stock of the traditional control was highly discrepant due to exceptionally high carbon concentration in all three subplots (Fig. 3). The main results are presented with and without the discrepant observation in order to show the influence of the outlier to the results. The analyses were performed using the MIXED and GLIMMIX procedures in version 9.3 of the SAS/STAT software (Littell *et al.*, 2006).

Results

Comparison of the improved management practices with their traditional controls

In 19 of the 23 plot pairs the difference in carbon stock was in favor of the improved practice (Fig. 3). Especially agroforestry and areas of restrained grazing had a clear positive impact on soil carbon stock compared with traditional management. Average carbon stock was in agroforestry plots 30% (95% CI: 4–64%) higher and in plots with restrained grazing 52% (95% CI: 12–106%) higher than in their adjacent, bordering traditionally managed plots (Fig. 4, Table 3). Correspondingly, the average carbon stock was 15% (95% CI: −15 to 57%) higher under terracing than the control (without one discrepant observation, Table 3). When averaged across the improved management practices their common relative gain was 32% (95% CI: 14–52%) higher than in the control plots (medians 26.0 and 19.7 Mg ha^{-1}, $P < 0.001$). The length of time the plot had been under improved management ranged from 6 to 20 years for agroforestry, from 6 to 17 years for restrained grazing and from 5 to 10 years for farmland terracing.

In our data, the bulk density differences were small within the matched pairs (Table 2) leading to a small difference in relative carbon stock gain by the improved managements between the fixed depth approach and the equivalent soil mass approach (Ellert & Bettany, 1995; Wendt & Hauser, 2013) indicated by the carbon concentrations kg per Mg soil (Table 4), and applied to assess the sensitivity of our results to the method used to quantify soil carbon stocks. Consequently, the differences in average carbon stock are not overestimated in this study.

Comparison of the improved management practices with each other

The differences in magnitudes of the carbon stock gains by the improved management practices do not necessarily reflect the difference in impact by the improved practices, but may result from the various conditions of the improved practices (e.g. cultivation history, soil texture, slope, and local precipitation) indicated by the difference of carbon stock levels of the traditionally managed control plots (Fig. 3). Furthermore, the carbon stocks depended slightly on the durations of the improved practices, tending to be lower with the longest durations than with the shortest durations. Consequently, to compare the improved practices in terms of their impact on soil carbon stock, it is essential to eliminate the effects of the differences in the sizes of the carbon stocks in the adjacent traditional plots and in the durations of the improved practices. To adjust for the differences in duration, the soil carbon stocks were divided by the duration (in years) of the improved practices and the ratio, i.e. the rate of carbon stock accumulation since conversion to improved management, was used as a response variable in a model where the corresponding carbon stock of the traditional management was included as a covariate to account for differences in the sizes of the carbon stocks of the traditional plots.

The relationship between the response and the covariate was modeled by a regression line allowing different intercepts and different slopes for the improved management practices. However, tests of the equality of the slopes and the equality of the intercepts of the regression lines revealed that a common regression line adequately fitted the data for each improved practice when one discrepant terracing observation was excluded (Fig. 5, Table 5). This result indicates that the differences in rate of carbon stock accumulation among the plots managed with improved practices are accounted for the corresponding differences of the traditional controls. The estimate of the common slope, 1.09 Mg ha^{-1} (standard error = 0.077), indicates that since conversion to improved management the average increase in the carbon stock accumulation rate of the plots managed by each improved practice is 1.09 Mg ha^{-1} for every 1.00 Mg ha^{-1} increase in the accumulation rate of the traditionally managed plots. When the discrepant observation was included in the analysis, the slope of the regression line for terracing deviated from the common slope of the lines for agroforestry and area with restrained grazing because the discrepant observation drew the line toward it (Fig. 5). This observation suggests that, under conditions of higher initial rate of soil carbon stock accumu-

Table 2 Selected physical properties for the matched plot pairs consisting of the plots of traditional and the improved management. The slope was qualitatively estimated as follows: 1 = gentle, 2 = medium, and 3 = steep. Clay denotes particles <0.002 mm, silt 0.002–0.06 mm and sand 0.06–2.0 mm in the fine earth (<2 mm). The proportion of gravel (>2 mm) was determined for the entire soil mass

				Particle size distribution in fine earth													
				Clay %		Silt %		Sand %		Gravel, %		Texture		Bulk density (g dm^{-3})		pH H_2O 1:2.5	
	Pair	Altitude, m	Slope	Imp.	Trad.	Imp.	Trad.	Imp.	Trad.	Imp.	Trad.	Imp.	Trad.	Imp.	Trad.	Imp.	Trad.
Agroforestry	1	1895	1	36	31	44	38	20	31	4	7	sicl	cl	1.30	1.30	7.8	7.5
	2	1895	1	49	46	37	31	14	23	4	3	c	c	1.24	1.28	7.9	7.4
	3	1871	1	33	33	56	56	11	11	1	0	sicl	sicl	1.28	1.25	8.1	8.0
	4	1970	2	29	47	34	23	37	30	18	12	cl	c	1.43	1.35	8.0	8.3
	5	2025	2	48	55	32	28	20	17	4	2	c	c	1.31	1.35	7.6	8.1
	6	2050	2	36	12	34	61	30	27	3	3	cl	sil	1.32	1.28	7.9	8.1
	7	2040	2	31	30	35	30	34	40	8	0	cl	cl	1.24	1.50	8.0	7.0
	8	2031	2	50	51	27	27	22	22	5	5	c	c	1.37	1.32	8.0	7.8
Restrained grazing	1	1763	3	19	14	37	26	44	60	19	27	l	sl	1.02	1.43	7.5	7.7
	2	1468	3	19	18	29	27	52	55	46	47	l	sl	1.05	1.06	7.8	7.7
	3	1455	3	19	20	35	42	46	38	28	47	l	l	0.98	1.00	7.7	7.7
	4	1426	3	21	16	32	33	47	51	23	36	l	l	1.01	1.14	7.8	7.6
	5	1519	3	15	11	37	29	48	60	17	4	l	sl	1.00	1.11	7.2	8.2
	6	1607	3	10	12	16	36	74	52	48	25	sl	l	1.25	1.26	8.1	8.4
	7	1526	3	14	10	26	25	60	65	31	33	sl	sl	1.30	1.33	7.9	7.9
Terracing	1	1998	2	19	7	33	23	48	70	24	39	l	sl	1.19	1.41	7.5	7.3
	2	1526	2	16	13	33	36	51	51	23	17	l	l	1.09	1.26	7.7	7.8
	3	1605	2	10	6	26	16	64	78	26	27	sl	ls	1.31	1.32	7.4	8.1
	4	1598	2	6	11	22	23	72	66	13	34	sl	sl	1.39	1.34	8.0	7.7
	5	1597	2	17	10	30	22	53	68	16	26	sl	sl	1.09	1.21	8.0	8.2
	6	1598	2	16	20	30	27	54	53	19	29	sl	scl	1.23	1.22	7.7	8.1
	7	1586	2	8	5	25	19	67	76	21	19	sl	ls	1.42	1.53	8.0	7.9
	8	1529	2	16	15	32	34	52	51	25	25	l	l	1.45	1.46	8.0	8.0

For texture: c, clay; sicl, silty clay loam; cl, clay loam; l, loam; sl, sandy loam; scl, sandy clay loam; sil, silt loam; ls, loamy sand.

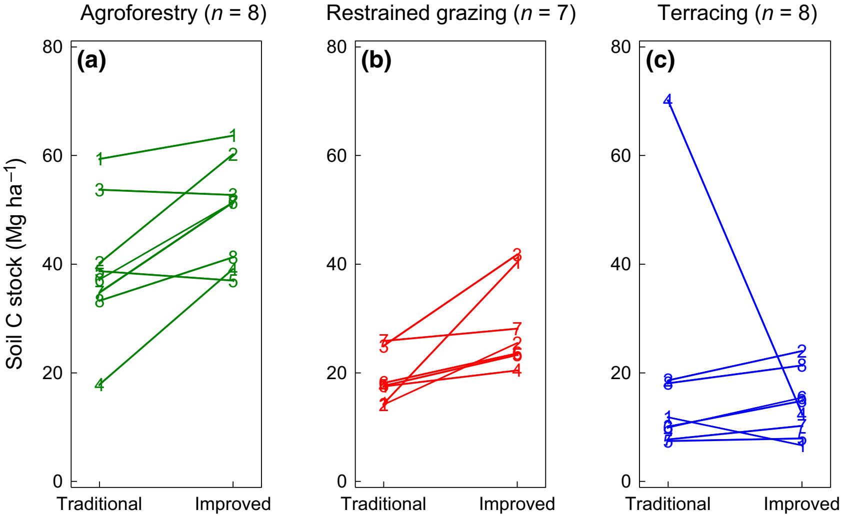

Fig. 3 The size of the soil carbon stocks in the plots with improved management practices [(a) agroforestry, (b) restrained grazing and (c) terracing] and their adjacent, traditionally managed plots. The inherent variability between and within field plot pairs is shown in the figure. The number of plot pairs is presented in parentheses.

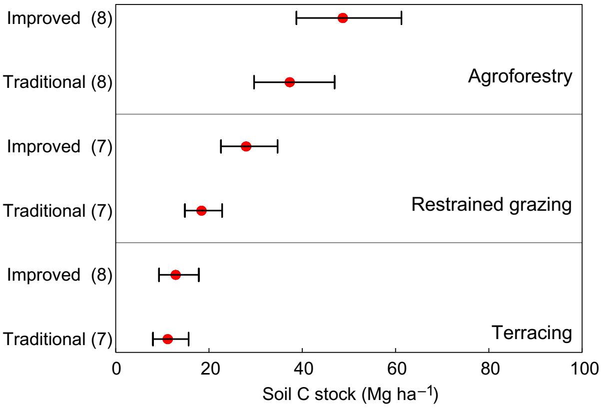

Fig. 4 Estimated median soil carbon stocks for the plots with improved management practices and their adjacent, traditionally managed plots with 95% confidence intervals for the medians. The estimates were based on data from which one discrepant value for a terracing traditional control (pair 4 in Fig. 3) was excluded. The number of replicated plots is presented in parentheses.

lation, the accumulation rate for terracing would not be as high as for agroforestry and restrained grazing.

Discussion

Explanatory factors for carbon sequestration potential

Agroforestry and restrained grazing had a greater stock of soil carbon compared with traditional management, but the difference was less obvious with terracing. The higher average carbon stocks under agroforestry and in areas with restrained grazing are partly explained by a higher biomass of perennial vegetation with multilevel canopy and root systems (Schlesinger & Lichter, 2001). In addition, the woody biomass and deposition of root biomass in deep soil layers as well as reduced soil disturbance slowed the decomposition of organic matter (Smith & Olesen, 2010).

The gains by the improved management depended also on the carbon stock levels in the adjacent traditionally managed plots and the durations of the improved practices. The carbon stocks were greatest for the traditional plots adjacent to the agroforestry plots reflecting the landscape with lower elevation, a notably shorter cultivation history, more diverse crop rotations, higher rainfall, and finer soil texture. In the regions where restrained grazing and terracing were practiced and where the carbon stocks were smaller than in the region of agroforestry, steep slopes were cultivated and grazed for thousands of years with a severe rate of degradation. In the freely grazed land, the noncultivation and grassland may have resulted in greater carbon stocks than in the cultivated fields. The gradual shifts in the positions of the terraces, due to frequent collapses, may have reduced the differences in carbon stock between the adjacent fields and thus hidden the possible impact of terracing through reduced soil erosion and exit of organic matter. An additional contributing factor may have been the mixing of carbon-scarce subsoil, and thus the dilution of the carbon-rich topsoil, when the terraces were established. After controlling for the differences in the carbon stocks of the traditionally managed plots and in the durations of the improved practices (and excluding the discrepant observation for terrac-

Table 3 Test results for the comparison of average soil carbon stocks under improved and traditional management practices without (and in parentheses, with) one discrepant traditional control value for a terracing pair (pair 4 in Fig. 3). The differences were tested on the log scale using two-sided *t*-type tests. Estimated means for the improved and traditional management practices were back-transformed to the original scale, and the differences between the resulting values (medians) are presented; *n* = number of plots, and df = degrees of freedom

		Soil C stock, Mg ha^{-1}				
Improved management practice	*n*	Range for traditionally managed plots	Difference (Imp.-trad.)	*t*-value	df	*P*-value
Agroforestry	16	18–59	11.4	2.73	7	0.03
Restrained grazing	14	14–26	9.6	3.36	6	0.02
Terracing	15 (16)	7–19 (70)	1.7 (−1.2)	1.11	7	0.31 (0.74)

Table 4 Estimated mean soil carbon stocks per equivalent soil mass, i.e., carbon concentrations (kg per Mg soil) for the plots with improved practices and their adjacent traditionally managed plots with 95% confidence intervals (CIs) for the means; *n* = number of replicated plots; relative gain (%) = [(Mean$^{\text{Improved}}$ − Mean$^{\text{Traditional}}$)/Mean$^{\text{Traditional}}$] × 100; one discrepant value for the traditional control in a terracing pair (pair 4 in Fig. 3) was excluded

			Soil C, kg per Mg soil		
Group of plot pairs	Management practice	*n*	Mean	95% CI for the mean	Relative gain (%)
Agroforestry	Improved	8	25.4	20.8–31.0	28
	Traditional	8	19.9	15.9–25.0	
Restrained grazing	Improved	7	18.0	14.3–22.8	68
	Traditional	7	10.7	7.9–14.6	
Terracing	Improved	8	7.5	5.5–10.2	29
	Traditional	7	5.8	4.0–8.3	

ing), the slopes of the regression lines, describing the relationship between the accumulation rates under the improved and the traditional management practices, did not differ among the improved practices. However, more research is needed to reliably determine the influence of the initial conditions on the carbon sequestration rate under the improved practices.

Comparison with previous studies

In the recent study of Gelaw *et al.* (2014) two improved practices (agroforestry and irrigation) were compared with treeless rain-fed cultivation. Although the mean difference in the carbon stock between agroforestry and the control (9.7 Mg C ha^{-1}) was not statistically significant, the estimate is of the same magnitude as for restrained grazing in our study. However, our estimates of average carbon sequestration under agroforestry and restrained grazing are higher than previously reported in process-modeling studies (Tschakert, 2004; Farage *et al.*, 2007 Smith *et al.*, 2008). For example, Tschakert (2004) reported tree plantation (*Faidherbia albida*) increasing soil carbon stocks during 25 years by 0.2 Mg ha^{-1} a^{-1}, Farage *et al.* (2007) through maintaining trees up to 0.1 Mg ha^{-1} a^{-1} in the top 20 cm and Smith *et al.* (2008) through agroforestry in warm-dry climate by 0.1 Mg ha^{-1} a^{-1}. In our study, under agroforestry, the accumulation rate in the top 15 cm was on average 1.2 Mg ha^{-1} a^{-1} (95% CI: 0.3–2.0) higher and in restrained grazing 0.7 Mg ha^{-1} a^{-1} (95% CI: 0.3–1.3) higher relative to the traditional control when estimated by the Hodges-Lehmann procedure (Sprent & Smeeton, 2001). The obvious reason for the difference is that the process-based models were developed and validated under temperate conditions and for systems not representative of East Africa (Andrén *et al.*, 2012). In previous studies from Kenya, the often-used soil organic carbon models Century and RothC performed better for monocropping than for intercropping systems common in East-Africa (Kamoni *et al.*, 2007), exemplified by the agroforestry and restrained grazing in the present study.

One additional explanation for the greater carbon sequestration rates suggested by the empirical results of the present study than by previous process-based modeling is that the severely degraded soils of East Africa are far from the carbon equilibrium state for the recently introduced improved management practices. This may explain the higher carbon accumulation rates in these soils during the initial stages after management transition represented by our results. This situation also seems to occur for agroforestry, as illustrated by the similarity of the slopes of the regression lines among the practices when the discrepant observation for terracing was excluded. The observation in the agroforestry data under the longest management duration, i.e., 20 years (the lowest green circle in Fig. 5) indicates a slowing carbon accumulation rate and supports distance from the steady state as one reason for the difference between our empirical results and the previous results obtained by process-based modeling.

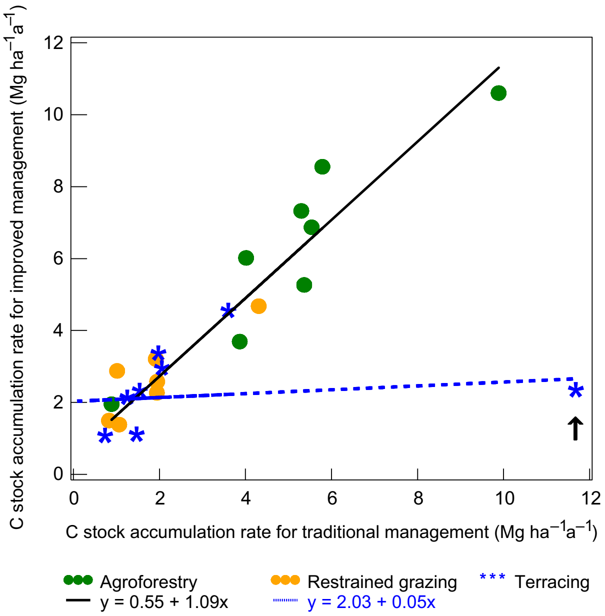

Fig. 5 Observed and modeled relationships between rates of soil carbon stock accumulation under the improved management practices and under the traditional practices since conversion to improved management. The carbon stock accumulation rates were calculated by dividing the carbon stocks by the number of years the plot had been under improved management. The common regression line for all of the three improved management practices (black solid line) is based on data from which one discrepant observation for terracing (shown by the arrow) was excluded. The discrepant observation drew the regression line for terracing toward it and affected the slope considerably (blue dotted line).

Efficiency of pair-matching

One commonly used sampling design in comparison of soil carbon stock between different management practices or land uses is to collect soil samples from independent field plots. However, the plots can differ in extraneous, unknown, and thus uncontrolled factors that could influence soil carbon stock (e.g. soil texture, soil fertility, precipitation, slope). A common way in field experiments to minimize the effect of uncontrolled plot-to-plot variation on the variance of the treatment comparisons is blocking, in which the plots are grouped into blocks so that the plots within each block are as alike as possible and are therefore expected to give nearly the same observation if the treatments are equivalent in their effect. Between blocks there can be substantial differences in plots. The effect of block differences is eliminated by making all treatment comparisons on the homogeneous plots within each block and then averaging these comparisons over blocks. In case of two treatments, for example, the differences between the observations of the treatments calculated for each block may be used as observations in the statistical

Table 5 Model simplification in analysis of covariance for the rate of soil carbon stock accumulation, under the improved management practices since conversion to improved management (y), with the corresponding accumulation rate of the traditional management practice used as a covariate (x). To investigate whether the initial model could be simplified, the following regression lines were fitted to the data: M1) different slopes and different intercepts for the regression lines of the improved practices (the initial model), M2) equal slopes and different intercepts for the improved practices, M3) equal slopes and equal intercepts for the improved practices. Management practice was included as a random cluster effect in the latter model. The results are presented without one discrepant terracing observation (pair 4 in Fig. 3); df = degrees of freedom

(a) Model equations

Management practice	M1	M2	M3
Agroforestry	$y = 1.20 + 1.00x$	$y = 1.22 + 1.00x$	$y = 0.55 + 1.09x$
Restrained grazing	$y = 1.10 + 0.83x$	$y = 0.79 + 1.00x$	$y = 0.55 + 1.09x$
Terracing	$y = -0.04 + 1.25x$	$y = 0.41 + 1.00x$	$y = 0.55 + 1.09x$

(b) Tested null hypotheses H_0

H_0	*F*-value	df	*P*-value	Conclusion
Equal slopes in M1	0.40	2, 16	0.67	Support for H_0
Equal intercepts in M2	1.17	2, 18	0.33	Support for H_0
Slope = 0 in M3	197.50	1, 18	<0.0001	Support for a positive linear association between the response variable and the covariate

analysis. The elimination in this way of the effect of part of the uncontrolled variation due to other factors than the management was the object of the pair-matching of the plots in our study. Because of the pair-matching the carbon stocks from the same plot pair were positively correlated, the intraclass correlation coefficient being 0.7 for terracing (without one discrepant plot pair), 0.6 for agroforestry, and 0.2 for restrained grazing. The positive correlations increase the precisions of the comparisons between the improved and traditional management practices, because the variance of the differences is smaller if the observations from the same plot pair are positively correlated than if they are uncorrelated (Koopmans, 1981). The relative efficiency of the pair-matching (determined as in Neter *et al.*, 1996) was 2.7 for terracing indicating that almost three times as many replications per management practice would have been required with an unpaired independent plot design to achieve the same variance for a mean difference in carbon stock between the improved and traditional management practices as was obtained with the matched pairs design. The relative efficiency of the pair-matching was 2.0 for agroforestry and 1.1 for restrained grazing. The matched pairs design was thus beneficial in our study.

In conclusion, the results for the comparison of the improved and traditional management practices in varying conditions show that Ethiopian agriculture has greater potential for soil carbon sequestration than previously estimated. Higher level for soil carbon sequestration compared with previous results is likely explained by the development and validation of the process models in temperate conditions, for monocropping and for conditions where soil carbon stock is closer to a new management-specific equilibrium than under improved management in Ethiopia. In data based studies all efforts to reduce the error variance are important in order to improve the power of statistical tests and the precision of estimates. Use of the matched pairs design is one possibility when feasible.

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