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Remediation of acid soils and soil property amelioration via *Acacia decurrens*-based agroforestry system

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Abstract Land degradation and the associated soil acidity are critical challenge for crop production in Ethiopian highlands. Since liming is expensive, farmers have developed an alternative agroforestry system by integrating *Acacia decurrens* into their landscapes. The expansion rate of this system was assessed over the last three decades. The effects of the agroforestry system and charcoal-making kiln sites on soil properties were investigated for over five years compared to the adjacent croplands. Soil samples were collected from *A. decurrens* plantations, kiln sites, and adjacent croplands at 0–15 and 15–30 cm soil depths. In the last 30 years, the plantation and croplands increased by 8% and 17.5%, respectively, compared to the land-use system in 1993, mainly at the expense of grassland and abandoned land. The main incentive for expansion of *A. decurrens* plantations was farmers' income generated from charcoal making. This intervention also improved soil properties with a significantly positive effect on soil pH, soil organic carbon (SOC), cation exchange capacity (CEC), and available Bray phosphorus (Bray-P) compared to the adjacent croplands. Results revealed that the SOC content in year 2 increased significantly (1.3–1.7 times) under *A. decurrens* plantation compared to adjacent crop fields. Moreover, soil pH increased by one unit on charcoal-making fields, which was equivalent to application of 4–5 t lime ha^{-1}, while SOC increased by ∼ 10% on kiln sites compared to the control. Charcoal making kiln spots increased available soil phosphorus by 112% compared to the adjacent non-kiln sites. The Bray- P was strongly and significantly ($P < 0.05$) correlated (r = 0.75) with soil pH. We conclude that integrating *A. decurrens*-based agroforestry practices would improve livelihoods by restoring degraded lands, improving income generation and carbon sequestration.

Keywords *Acacia decurrens* · Carbon sequestration · Charcoal making · Soil acidity · Soil heating · Soil properties

Introduction

Land degradation is a critical challenge, substantially affecting agricultural productivity and rural livelihoods in Ethiopia (Amede et al. 2020; Agegnehu and Amede 2017), contributing its part to the current

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complex ecological, economic, and social issues (Agegnehu and Amede 2017; Tittonell and Giller 2013; Vanlauwe et al. 2015). It is especially serious in the highlands, which is 44% of the total area of the country where human and livestock pressure is high (Amede et al. 2001). The major causes of land degradation in Ethiopia include excessive removal of biomass, particularly crop residues for livestock feed (Hurni et al., 2015; Amede and Taboge 2007), inadequate nutrient recycling to return some nutrients to the source (Agegnehu and Amede 2017; Amede and Kirkby 2004), an annual average soil loss rate of 42 t ha^{-1} for croplands and up to 300 t ha^{-1} per year (Hurni et al. 2015), with the most vulnerable landscapes in soil loss and nutrient mining being high slope farms (Amede et al. 2020).

Soil acidity is one of the major constraints of crop production in the high rainfall areas of Ethiopian highlands, which affected 41% of the cultivated land (Schlede 1989). In Ethiopia, loss of crop yield due to soil acidity ranges from 20 to 80% depending on the degree of acidity, agronomic practices, and agro-ecology (Regassa and Agegnehu 2011). Soil acidity could be the result of high rainfall accompanied by the leaching of nutrients, cation mining due to the growing of high yielding crops, acidic soil parent material, and application of acidifying fertilizers and a combination of these factors (Goulding 2016; Pearson 1975; Xu et al. 2020). Acid soils commonly fix phosphorus and making it unavailable for plant growth (Duncan 2002), caused by the loss of exchangeable cations including Ca and Mg and reduced cation exchange capacity of the soil (Fageria and Nascente 2014; Goulding 2016). Crop yield is usually very low in strongly acid soils due to the possible Al and Mn toxicities (Barber et al. 1988). Moreover, soil acidity restricts the choice of crops that could grow in the farming system (Fageria and Nascente 2014; Haile and Boke 2009), thereby affecting crop rotation and diversification of crops. Severe acidification could also cause non-reversible clay mineral dissolution and structural deterioration (Abebe 2007).

For instance, in Gojjam, one of the productive areas of the country, soil acidity is becoming the major production constraint. Nitisol are the dominant soils in the area, with high precipitation of Al phosphate and soil acidity (Agegnehu 2018; Golla 2019). Soil acidity in our study sites of Gashena Akayita, Enguti, and Enerata, were found to be below 5.0 in soil pH, with a significant exchangeable Al^{3+} concentration (Abate et al. 2017). Demil et al. (2020) also reported over 4 centimol kg^{-1} exchangeable acidity of soil in neighboring Machakel district.

Although the Amhara region in northern Ethiopia used to be a high potential area for wheat, barley, and faba bean production, crop productivity has significantly decreased in these highlands to the level that significant numbers of farmers are slowly abandoning cereal farming (Demil et al. 2020). Various interventions, including application of lime, have been found to be effective in minimizing the negative effects of soil acidity (Agegnehu et al. 2018; Golla 2019), but lime is not readily available to farmers at the required amount and affordable price. Consequently, farmers have shifted their farming from growing annual crops to planting trees, such as *Eucalyptus spp*. as a cash crop owing to source of livelihood for most households and very low yield of crops (Wondie and Mekuria 2018; Dessie et al. 2019). The coverage of Eucalyptus has vastly expanded around the rural towns following high demands for fuelwood, construction, and wood products (Wondie and Mekuria 2018).

A new and innovative farming system has emerged in the last few years by integrating *A. decurrens* plantation as an agroforestry practice in Gojjam area (Wondie and Mekuria 2018; Nigussie et al. 2021). The plantation started in the degraded and acid soil areas where annual crop production has been deteriorating over years. This is farmers' innovation, which has been started in Fagta-Lekoma district and expanding to the neighboring districts, including Banja, Dangla, Akasha, Gozamin, and Sekela at a large scale with limited involvement of government extension or non-government organizations. *Acacia decurrens* are tolerant to frost (Hakim and Miyakawa 2015) and adapted to the various soil types (Mekonnen 2007). Farmers have developed an agroforestry system, whereby they grow *A. decurrens* in a five-year rotation, which is then harvested for charcoal production, and the litter including the remains of the fine charcoal material is left in the field to be incorporated into the soil to ameliorate degraded soils. In the first two years of plantation, crops or livestock feed could be grown with the trees as intercrops. However, starting from year three, only trees are grown in a high density with high canopy cover.

Generally, charcoal production in the country is using traditional earth-mound kilns. In *A. decurrens* plantation areas, where charcoal making is done within the farm, in different parcels, and in rotation, there is limited evidence on the potential effect of charcoal production on soil properties. Earlier reports (Lehmann and Rondon 2006; Steiner 2007) indicated that charcoal making would improve soil fertility and ultimately crop yield. However, the new and large-scale *A. decurrens* plantation brought about a landscape transformation although its effect on soil properties is not yet well established. Therefore, this research was initiated with the following objectives: 1) to assess land use land cover changes over time and determine the rate of expansion of *A. decurrens* in the last three decades; 2) evaluate the effects of different ages of *A. decurrens* plantation on soil properties compared to adjacent croplands; and 3) determine the aftereffect of on-farm charcoal production on selected soil properties.

Materials and methods

The study area

The research area is situated in the northern part of Ethiopia, Awi zone of the Amhara region (Dangila, Fagta-Lekoma, and Banja districts) (Fig. 1). It lies between the longitudes of 36.45^0 E and 37.14^0 E and the latitudes of 10.71^0 N and 11.48^0 N. Injibara is the administrative center of Awi and falls inside the present study area. The zone is characterized by very high and unimodal rainfall, with an average annual rain-fall and temperature of 2435 mm and 20 °C, respectively (Nigussie et al. 2016). High soil degradation characterized by soil acidity and low crop productivity has been the major challenge of agricultural production and food security. The farming system is a mixed crop-livestock and subsistence-oriented system with increasing shift towards agroforestry systems (Wondie and Mekuria 2018*).*

Data from the Landsat series of satellites, with a spatial resolution of 30 m was used for classification and estimating land use land cover change (LULC). One image from the dry, non-growing season of Ethiopia (January–February) was considered for classification for each of the four years. The details of the data used are given in Table 1. The Level 1 Landsat images were converted to Top-of-Atmosphere (TOA) reflectance images using the appropriate values from the product metadata. Normalized Difference Vegetation Index (NDVI) was computed for each image and stacked along with six bands of the TOA images (blue, green, and red, NIR, SWIR1, and SWIR2). Unsupervised Isodata clustering was applied to the stacked images to classify each image into 40 classes. Similar classes were merged and the final images with a classification scheme of seven classes (Dense vegetation, Cropland with sparse shrubs, Plantations, Grass cover, Barren/fallow–wet/overturned soil, Barren/fallow—dry, and other classes like water and built-up) were created. The seven classes were chosen based on their signatures in Landsat False Color Composite (FCC) images and by referring to very high-resolution data from Google Earth. It was seen from the classification results those plantations were present in a large number in the central part of the study area in 2019, which were absent in 1993 and 2001. In order to map these plantations, Sentinel-2 satellite data of 6 February 2019 was used to augment the Landsat images (Table 1). Level 1C products of Sentinel-2, which provide the TOA reflectance data, were used. Knowledge-based rules were applied to the stacked image to extract plantation-covered area. Ground truthing was done through transect walk.

Soil sampling procedure and analysis

Soils from different ages of *A. decurrens* and the adjacent cropland were compared for key soil parameters. Five sites that had different ages of plantations, i.e., Year 0 (Y0), Year 1 (Y1), Year 2 (Y2), Year 3 (Y3), and Year 4 (Y4), and the adjacent cultivated cropland as a control were selected for soil sampling. Year 0 represented soil samples collected from plantations less than 12 months of age; Year 1- soil samples collected from plantations older than one year but less than two years; Year 2—soil samples collected from plantations older than 2 years but less than 3 years; Year 3—soil samples collected from plantations older than three years but less than four years; Year 4—soil samples collected from plantations older than four years; and the control represented soil samples collected from adjust cultivated croplands. Four soil samples per age of the plantation, four samples per cropland, and 20 samples per site were collected. A total of 96 soil samples were collected at 2 depths (0–15 cm and 15–30 cm), along with soil core samples for the determination of bulk density.

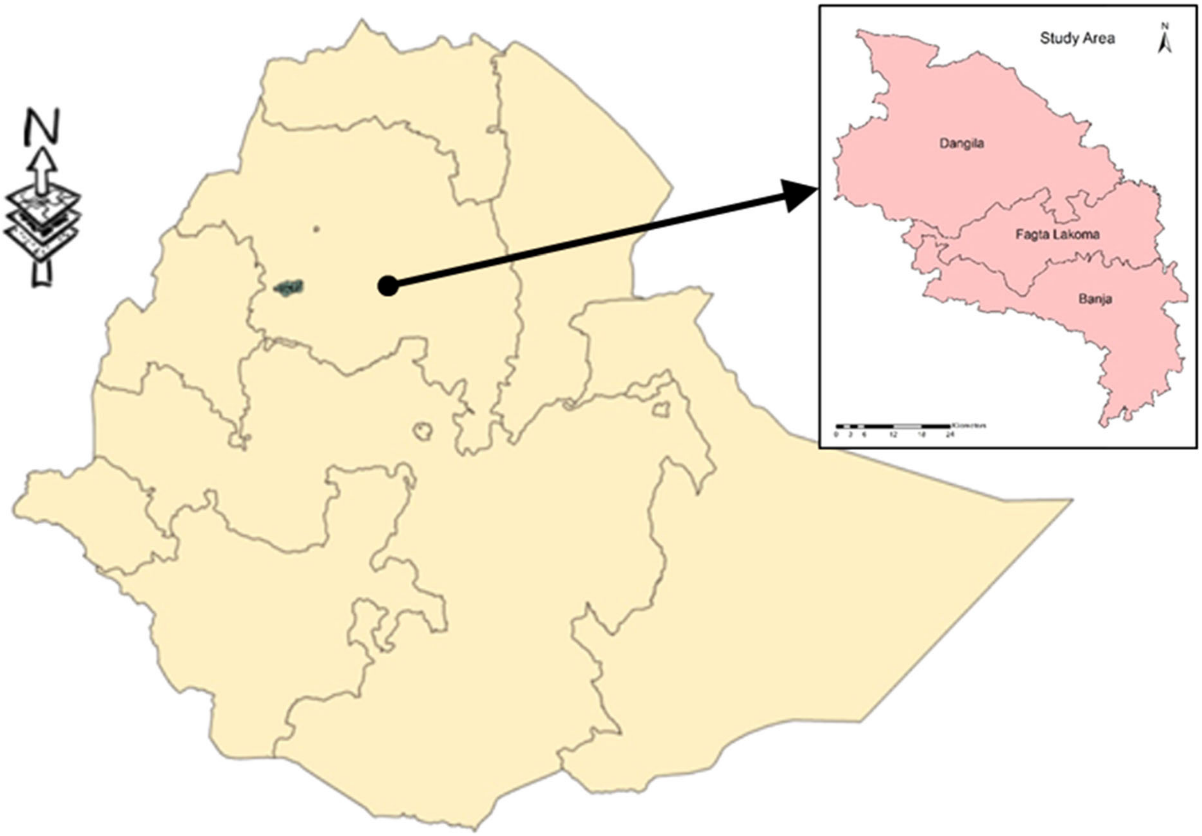


Fig. 1 Location of the study site in Awi zone, north-western part of Ethiopia

Twenty-five charcoal-making spots per ha were selected, with a total area of 1026 m^2. The shape of charcoal production sites (kilns) was circular (Fig. 3) with a radius of 3–4.2 m and a mean of 3.6 m. Five years old *A. decurrens* trees were cut, dried, and cut into pieces, piled together using a traditional kiln method (earth mound or pits) and covered with leaves and twigs, and then covered with soil allowing thermal decomposition under oxygen-deprived conditions. The temperature for traditional kiln method is estimated to be of 400-500^{0}C (Adam 2009; Brown 2009). The resulting charcoal was collected in sacks, and the finer ones are left in the field and incorporated to $\sim$ 10–15 cm depth using a hand hoe. We measured the area of cleared plantation sites used for charcoal-production in each farm. The numbers of kilns per site were counted and their corresponding area was calculated based on the formula of the circle: $\boldsymbol{A} = \pi \boldsymbol{r}^2$ as the shape of charcoal producing kilns are circular. Where A = area of charcoal making points, π = 3.14, and r is the radius of the kilns. Finally, areas of kilns were added together and the proportion of the kiln area to the total area of the plantation cut for charcoal production was determined for each study site.

To evaluate and quantify the effect of charcoal production on soil properties, soil samples were collected from charcoal making spots. Ten soil sampling points were selected from recently harvested and charcoal producing sites of *A. decurrens*. For a clear presentation of the general procedures of charcoal production, its associated activities are shown in Fig. 3. From each site, four soil samples (two from charcoal producing kilns and two from adjacent non-charcoal producing sites) were collected using auger at 0–15 and 15–30 cm depths for the analysis of soil physiochemical properties, including soil organic carbon (SOC), available Bray and Olsen-phosphorus (Bray-P and Olsen-P), and soil bulk density. Leaf litter, charcoal, and other plant debris were removed before soil sampling and are parts of the research. The finer roots and other plant parts were separated

Table 1 Details of datasets used for land use land cover change study

Year	Satellite	Bands	Date of acquisition	Spatial resolution
1993	Landsat 5 TM	Band 1 – Blue Band 2 – Green Band 3 – Red Band 4 – NIR Band 5 – SWIR 1 Band 7 – SWIR 2	06th January, 1993	30 m
2001	Landsat 7 ETM +	Band 1 – Blue Band 2 – Green Band 3 – Red Band 4 – NIR Band 5 – SWIR 1 Band 7 – SWIR 2	05th February, 2001	30 m
2014	Landsat 8 OLI	Band 2 – Blue Band 3 – Green Band 4 – Red Band 5 – NIR Band 6 – SWIR 1 Band 7 – SWIR 2	01st February, 2014	30 m
2019	Landsat 8 OLI	Band 2 – Blue Band 3 – Green Band 4 – Red Band 5 – NIR Band 6 – SWIR 1 Band 7 – SWIR 2	30th January, 2019	30 m
2019	Sentinel-2	Band 2 – Blue Band 3 – Green Band 4 – Red Band 8 – NIR	06th February, 2019	10 m

carefully from each soil sample, cleaned, and weighed. The samples were air-dried under the shade, ground using a pestle and mortar, and sieved to pass through a 2 mm sieve. The soil samples were analyzed for chemical properties at the soil, plant, and water analysis laboratory of Adet Agricultural Research Center in Ethiopia. Soil pH was determined in a 1:2.5 soil to water suspension following the procedure of Sertsu and Bekele (2000). The organic carbon content was determined by the wet digestion method using the Walkley and Black procedure (Nelson and Sommers 1996). Available phosphorus was determined following the Olsen procedure (Olsen and Sommers 1982) and Bray method according to Sertsu and Bekele (2000). The cation exchange capacity (CEC) was determined after the extraction of the samples with 1 N ammonium acetate at pH7 (Sertsu and Bekele 2000). The soil moisture content was determined following a gravimetric procedure.

Statistical analysis

The effect of independent variables including the age of *A. decurrens* plantations and charcoal kilns on soil properties was statistically tested. The data were subjected to analysis of variance using the general linear model (PROC GLM) procedure of one-way-ANOVA using SAS statistical package version 9.3 (SAS Institute Cary, NC). Graphical presentations were performed using the PDIFF STDERR option in the LSMEANS statement of the GLM procedure of SAS, where error bars represent ± 1SE.

Results

Land use land cover change

The LULC analysis showed that Awi zone went through a significant landscape transformation over the last 30 years (Table 2, Fig. 2). The satellite images showed a significant shift from the conventional crop production system to an integrated agroforestry system, with increasing vegetative cover in the last 16 years (Fig. 2). For instance, the crop cover decreased significantly from 43% in 1993 to 8.4% in 2001 but recovered again to 71% in 2019 (Table 2). A corresponding reversal in trend is observed in grass-covered and barren areas. These barren areas collectively occupied 48% of the total area in 1993, which increased to 73% in 2001. But by 2014, this area had decreased to 60% of the total area, and to 29% by 2019. Most significantly, between 1993 and 2019, plantation increased from 0% to 8.1%, while cropland increased from 28 to 45%, respectively, mostly at the expense of barren lands and grasslands. The major driver of landscape change is the introduction of *A. decurrens* into the farming systems. Besides, according to the dense vegetation captured by Landsat images, there has been a significant increase in household woodlots, particularly around homesteads, on roadsides, and around cities where the charcoal demand is growing at a very fast rate (Abate et al. 2017).

Effects of different ages of *A. decurrens* plantation on soil properties

Results showed that both the physical and chemical soil properties, including soil bulk density, soil moisture content, soil organic carbon (SOC) content, and cation exchange capacity (CEC) significantly ($P < 0.05$ and $P < 0.01$) varied between the two soil depths regardless of the ages of the plantation (Table 3). *Acacia decurrens* planting age significantly ($P < 0.5$) improved soil bulk density, soil moisture content, pH, SOC, and CEC compared to the control (cultivated cropland) at 0–15 cm soil depth (Table 3). The parameters followed the same trend at the 15–30 cm soil depth, except for soil bulk density and soil pH (Table 4). Soil pH in the surface soils increased from 4.95 to 5.35 in just three years. The SOC content under different ages of *A. decurrens* plantation increased 1.5–1.7 times at the 0–15 cm and 1.3–1.5 times at the 15–30 cm soil depth compared to the adjacent control crop fields (Table 4). The highest soil moisture content of 24.7% and SOC content of 3.0% were obtained from year 2. Despite the

Table 2 Land use classes, area coverage and proportions of the study area in Awi zone, Ethiopia

Land use class	Area ('000 ha)			
	1993	2001	2014	2019
Dense vegetation	18.6	11.3	20.21	19.7
Plantations	0	0	0	12.79
Sparse vegetation/shrub	43.4	8.4	30.6	71.1
Grass cover	19.4	23.7	11.6	8.5
Barren/fallow-wet/overturned soil	14.7	50.4	47.2	3.5
Barren/fallow-dry	61.6	63.9	47.6	42.0
Others	0.05	0.03	0.57	0.36
Total area	157.8	157.7	157.8	157.9
Proportion of total area (%)				
Dense vegetation	11.8	7.2	12.8	12.5
Plantations	0.0	0.0	0.0	8.1
Sparse vegetation/shrub	27.5	5.3	19.4	45.0
Grass cover	12.3	15.1	7.4	5.4
Barren/fallow-wet/overturned soil	9.3	32.0	29.9	2.2
Barren/fallow-dry	39.0	40.5	30.1	26.6
Others	0.03	0.02	0.36	0.23

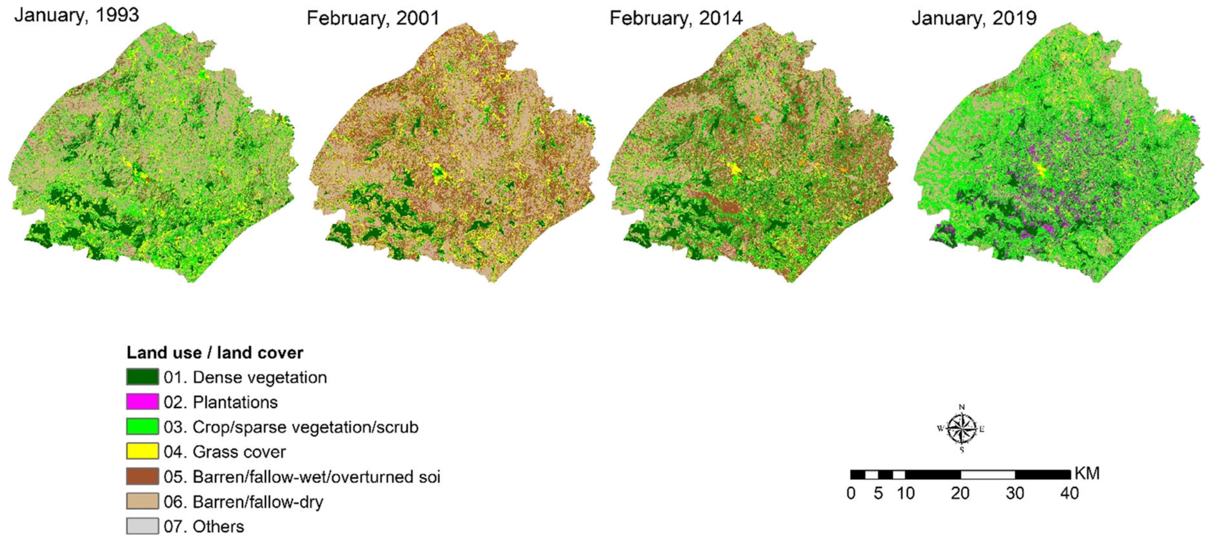


Fig. 2 Land use and land cover change in Awi zone of the Amhara Region, Ethiopia (1993–2019)

noticeable increase in SOC and moisture content of the soil due to the different ages of *A. decurrens*, the increments were not significantly different after year 2 compared to year 0. In contrast, the highest CEC of 34.6 and 35.2 cmol (+) kg^{-1} were recorded in Y4 plantation, both at 0–15 cm and 15–30 cm soil depths (Table 4).

Effect of charcoal making kiln sites on soil properties

The process of charcoal making is presented in Fig. 3. Farmers produce charcoal from the 5 years old *A. decurrens* trees directly on farmlands and by rotating charcoal-making mounds, or earthen pits. They deliberately rotate the mounds to different parcels to improve soil fertility across the farms. The number of the charcoal-making spots was 25 ha^{-1} with a total area of 1026 m^2 (10.3% of a hectare), which is a significant proportion. During harvesting, farmers leave a significant amount of leaf debris and fine charcoal materials or black carbon on their farms (Fig. 3), which would further enhance soil organic carbon content and nutrient stock.

Charcoal making kiln sites significantly ($P < 0.01$) improved soil pH, SOC, Bray-P, and Olsen-P at 0–15 cm soil depth, but at deeper depth, the effect was none significant except for P (Table 3). The change in P content due to charcoal making kiln sites was significant ($P < 0.01$) for both soil depths (Table 3). Bray-P was significantly higher for heated kiln spots than for unheated spots (Fig. 4). Available soil Bray- P from charcoal making kiln sites increased by about 112% at the surface soil depth of 0–15 cm, compared to the control with no-charcoal making adjacent sites. In contrast, charcoal making resulted in an increase of 100% available Bray-P and 0.30 units in pH over the control at 15–30 cm soil depth (Fig. 4). Charcoal making kiln sites effects on soil pH were pronounced mainly on the surface soils of 0–15 cm (Table 3) by a unit that is about a similar effect of 4 t lime ha^{-1}. Although variations were observed in soil pH at 15–30 cm soil depth the differences were not statistically significant. Interestingly, charcoal making kiln sites had a similar positive effect on SOC content at both soil depths, where $\sim$ 9.8% and $\sim$ 9.5% increases in SOC at 0–15 cm and 15–30 cm soil depths, respectively compared to the non-kiln sites (Fig. 4). The SOC and soil Bray-P were strongly and significantly ($P < 0.05$) correlated with soil pH (r = 0.75) and (r = 0.49), respectively (Fig. 5). On the other hand, charcoal-making kiln did not have significant effect on soil bulk density at both soil depths.

Discussion

Soil acidity, which covers about 43% of the agricultural landscape in Ethiopia (Agegnehu et al. 2018), is

Table 3 Significance of the effects of site, soil depth, plantation age, and charcoal making kiln sites on soil properties

Source of variation	Bulk density (g cm^{-3})	SMC (%)	Soil pH	SOC (%)	Bray-P1 (mg kg^{-1})	Olsen-P (mg kg^{-1})	CEC (cmol(+)
Site							
P level	**	*	**	***			***
MSE	0.01	33.5	0.05	0.36			25.3
CV	10.7	23.6	4.2	23.4			15.2
Soil depth (0–15 and 15–30 cm)							
P level	ns	***	*	*	***	***	ns
MSE	0.02	30.8	0.05	0.57	29.1	5.14	33.6
CV	11.7	22.6	4.5	27.3	25.2	25.2	17.6
Planting age (0–15 cm)							
P level	*	*	*	*			*
MSE	0.01	21.4	0.05	0.43			24.7
CV	7.0	20.6	4.5	23.9			15.1
Planting age (15–30 cm)							
P level	ns	*	ns	*			*
MSE	0.03	21.5	0.04	0.46			37.0
CV	14.5	17.2	4.0	27.6			18.4
Charcoal making sites (0–15 cm)							
P level	ns		**	*	***	***	
MSE	0.01		0.48	0.29	70.5	9.05	
CV	10.0		13.1	19.3	29.8	30.1	
Charcoal making sites (15–30 cm)							
P level	ns		ns	ns	**	**	
MSE	0.01		0.07	0.38	3.42	22.3	
CV	8,8		5.3	27.0	23.0	24.7	

Significant at $^{*}p \le 0.05$, $^{**}p \le 0.01$, $^{***}p < 0.001$; ns: not significant. MSE: Mean square error; CV: Coefficient of variation

considered as a major production constraint, particularly in high rainfall, highly productive Nitisol areas of the Ethiopian highlands. Subsistence farming is a common practice in the study area, where crop productivity has decreased due to land degradation, poor access to knowledge and technologies (Hurni et al. 2015; Zeleke et al. 2010). Generally, the application of mineral fertilizers has been the major strategy to increase crop yield, which became less effective due to increased soil acidity. In these acidic Acrisol and Nitisol areas, crop yield is becoming stagnant regardless of the rates of NP fertilizer application (Agegnehu and Amede 2017). An integrated soil fertility management that suits local biophysical, social, and economic realities has been developed by farmers, mainly by including *A. decurrens* plantation in the rotation cycles for up to five years, until the plantation is suitable for charcoal making (Abate et al. 2017; Wondie and Mekuria 2018) followed by cereal production.

Drivers of land use and land cover change

The results showed that the farming systems of Awi zone have changed towards a sustainable agroforestry system within 20 years of time from a purely crop-livestock-based farming system to a completely new integrated agroforestry-based system. The traditional

Table 4 Effect of *A. decurrens* planting age on soil bulk density, moisture content (SMC) (%), soil pH, organic carbon (OC), cation exchange capacity at two soil depths

	Soil depth (0–15 cm)				
	Bulk density (g cm^{-3})	SMC (%)	Soil pH	OC (%)	CEC (cmol (+) kg^{-1})
Planting age					
Control	1.26a	18.2b	4.95b	1.77b	29.8b
Year 0	1.24a	21.9ab	5.13ab	2.58ab	30.7b
Year 1	1.19ab	23.3ab	5.18ab	2.79a	33.8a
Year 2	1.19ab	24.7a	5.29a	2.99a	33.2a
Year 3	1.16ab	20.2b	5.35a	2.86a	31.9ab
Year 4	1.12b	23.5ab	5.24a	2.85a	34.6a
LSD (0.05)	0.10	4.2	0.24	0.62	3.5
Planting age	Soil depth (15–30 cm)				
Control	1.23	22.8b	5.20	1.75b	29.2b
Year 0	1.18	26.3ab	5.21	1.81b	30.8ab
Year 1	1.20	28.9a	5.38	2.43ab	34.7ab
Year 2	1.13	28.4a	5.22	2.62a	33.4ab
Year 3	1.20	27ab	5.27	2.69a	32.1ab
Year 4	1.08	27.7a	5.25	2.65a	35.2a
LSD (0.05)	0.16	4.20	0.19	0.65	5.9

Control: soil samples from adjust croplands; Year 0: soil samples from plantations less than 12 months; Year 1: soil samples from plantations older than one year but less than two years; Year 2: soil samples from plantations older than 2 years but less than 3 years; Year 3: soil samples from plantations older than three years but less than four years; Year 4: soil samples from plantations older than four years. Within a column, means followed with different letters are significantly different at $p < 0.05$. LSD: least significant difference

potato, wheat, and teff-based farming systems have integrated perennial trees at farm and landscape levels. Farmers innovated these practices with little extension support from local or national government.

Lack of household energy became a major driver of LULC in Ethiopia and charcoal production is widespread as the source of household energy. Participatory assessment in the drivers of change for planting *A. decurrens* indicated that increased plantation was strongly linked to decline in crop yield and increased demand for charcoal in major towns (Abate et al. 2016; Nigussie et al. 2021; Wondie and Mekuria 2018) though soil fertility decline has also been reported (Nigussie et al. 2017). In our study, 8% increase in plantation between 2014 and 2019 (Fig. 2) was mainly due to the expansion of *A. decurrens* which has positively influenced livelihoods in the area, with increased income at household and community level (Abate et al. 2017; Wondie and Mekuria 2018; Nigussie et al. 2017).

Effect of age of *A. decurrens* on soil properties

While the variation in the soil characteristics was not consistent with plantation ages, our findings showed that the plantations resulted in significant effect on soil characteristics compared to the adjacent crop fields (Table 4). However, the great anticipated change in soil organic matter did occur on Y2 but did not change much afterward due to the limited understory growth given the high density of acacia trees, with about 16,270 trees ha^{-1} (Nigussie et al. 2016). This could be also explained by the fact that farmers grow plantations on less fertile farms while reserving the fertile farms for growing crops. This could however change after repeated rotations.

Another study (Lehtonen et al. 2020) in Ethiopia indicated that soil organic carbon under acacia-based forests had about three times less soil organic matter content compared to the moist Afro-montane (MA) forest biome, mainly due to the limited litter under the

Fig. 3 Charcoal production and associated activities**.** Numbers in the Figure show: (1) Harvesting of plantation at the age of year 5, (2) leaf-debris, (3–6) charcoal production process, (7) charcoal marketing, (8) soils after charcoal production, and (9) plowing after 5 years of plantation for growing annual crops together with *A. decurrens* as agroforestry

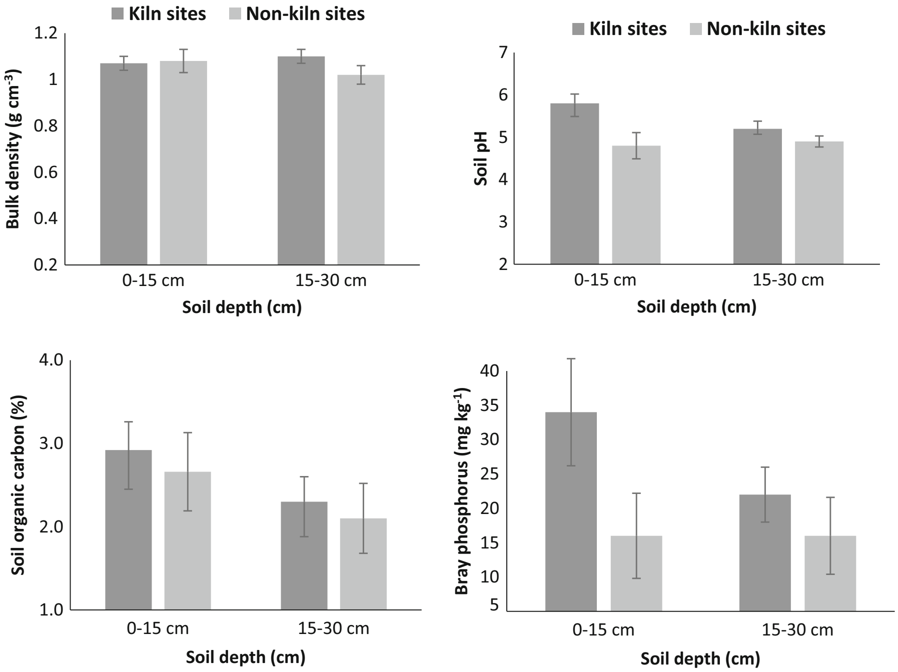
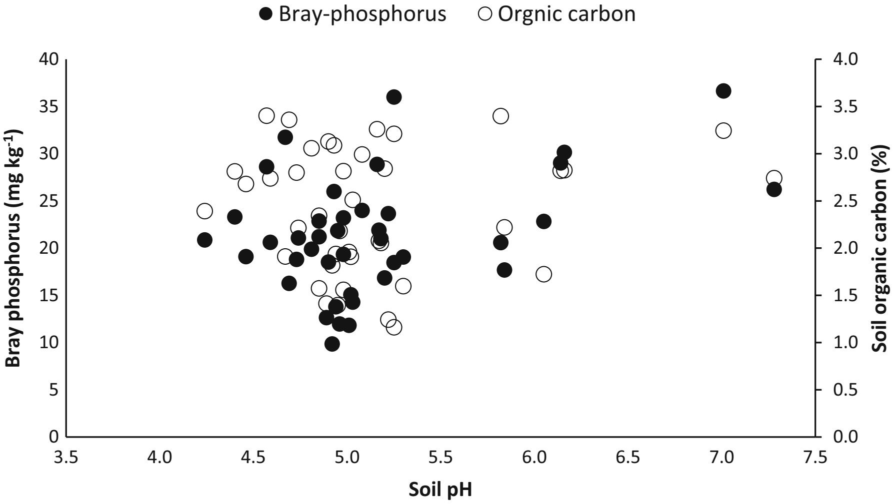


Fig. 4 The effect of charcoal making kiln sites (soil heating) on selected soil properties at 0–15 and 15–30 cm soil depths. Error bars represent ± 1SE

Fig. 5 The relationship between soil pH, phosphorus (mg kg^{-1}), and soil organic carbon content (%) under charcoal production Kiln sites and the adjacent non-kiln areas



canopies of acacia. Although Mekonnen (2007) found substantial soil fertility improvement due to the input of about 6 kg foliage per *A. decurrens* tree, we did not find significant difference in soil fertility between *A. decurrens* based soils and control plots after Y2. The increase in pH under plantations at 0–15 cm soil depth in Y2 could be explained by increase in CEC and Organic Carbon (Table 4) owing to residual litter and understory effects at the early ages of the plantations.

The major positive effect of growing *A. decurrens* on soil properties occurred when the trees were cut at Y5 for charcoal making and when all the leaves, branches, and other litters were left on the surface of the soil as mulch (Fig. 3). The leftovers of the biomass and the finer charcoal or black carbon materials were not part of the analysis and hence additional benefits may literally exist. Other studies (Edwards and Arancon 2004; Steven et al. 2009) showed a significant increase in soil organic carbon and earthworm population due to acacia mulch.

Effects of on-farm charcoal making sites on soil properties

The use of the earth mound kiln is the prevailing method for charcoal production throughout the community. On one hand, soil heating associated with charcoal production is a concern because of anticipated changes in microbial composition and function, greenhouse gas emission, soil C content, soil mineralogy, and water repellency and infiltration following severe burning (Neary et al. 2005). On the other hand, soil heating was reported to enhance nutrient availability and crop yield (Moritsuka et al. 2001). According to Oguntunde et al. (2008), the saturated hydraulic conductivity of soils under charcoal kilns increased significantly from 6.1 ± 2.0 cm h^{-1} to 11.4 ± 5.0 cm h^{-1}, resulting in a relative increase of 88%, and bulk density on charcoal-site soils reduced by 9% compared to adjacent field soils. Glaser et al. (2002) suggested that the use of a slash-and-char technique could be an alternative to the slash-and-burn system due to the proven positive impacts of charcoal additions on soil properties and productivity.

The benefit of charcoal making kilns was particularly apparent in tropical soils, which are generally acidic ($pH < 5$) and composed mainly of kaolinite clay, oxides, and hydroxides of iron (Fe) and aluminum (Al), sesquioxides (Thomaz 2017) causing aluminum toxicity and phosphorus fixation. Although the major objective of charcoal making was to generate household income, farmers quickly observed the positive effect of charcoal production on soil fertility improvement and yield increase on subsequent crops. Charred plant remains could contribute to soil organic carbon formation, of which the significant part of this black carbon could be converted to inert aromatic carbon (Goulding 2016). The increase in soil organic carbon and soil pH could be due to the remains of finer charcoal materials or black carbon that were incorporated in the soil after charcoal production. Kitur and Frye (1983) reported that heating Alfisols and Mollisols above 200^{0}C increased soil pH and enhanced extractable ammonium and CEC. The study of Thomaz (2017) also indicated that pH increased by 37% linearly at the highest temperature of 650 °C compared to the unheated soil in acidic tropical soils. The significant increase in pH (Fig. 4) due to heating could be explained by increased soluble carbonates and oxides (ash) formed during the charring process and a partial recovery of basic cations in the soil system (Goulding 2016), while also causing a decrease in Al content with increasing heat (Thomaz 2017) that might be the cause for the increased available P (Fig. 4). The increase in P uptake could be explained not only by the immediate increase of the water-soluble P concentration but also by the dissolution of Ca-bound P and the hydrolysis of water-soluble organic P in the rhizosphere (Moritsuka et al. 2001). According to Robinson et al. (2018), the burning of plant-based residues generated an increased proportion of hydroxyapatite (HAP) and pyrophosphates in the black carbon or charcoal. The total P contents of most plant feedstock charcoals were similar to that of green waste compost. Moreover, in acid soil, the dominant form of P in the charcoal (HAP) is likely to be more soluble than that found in green waste compost as well as in the charcoal feedstock (phytate). Thus, charcoals produced from lignocellulosic plant residues could be considered as an alternative P source for P-deficient, acid soils in low-input agriculture, and to supplement their other beneficial effects as soil amendments, in respect to soil pH, cation exchange, and water holding capacity (Robinson et al. 2018).

Although the increase in heat is expected to reduce soil organic matter (Thomaz 2017), we did not find a significant reduction in SOM due to heating, partly because the burning intensity was light given the charcoal making process that suppressed oxygen supply and the shorter time required to burn 5 years old young slash piles (Adam 2009). However, additional research is required to prove improved charring method targeting soil amendment through increasing black carbon and to establish the soil recovery period following charcoal making without affecting the income of the farming community. Because this would help farmers restore the fertility of their farmlands and increase crop productivity. Moreover, the analysis for the number of charcoal-making points as well as its area coverage was based on only the first single harvest and hence, we were not able to establish the long-term effects of charcoal making on crop yield and soil quality. However, the trend is that charcoal making practice is expected to recur at least every five years on the same farms that would increase the density of charcoal making points and associated positive effects on the soil properties. The integration of *A. decurrens* in other locations may require the understanding of the socio-economic and landscape niches, where farm-level plantation could bring about significant benefits with limited system trade-offs (Amede and Kirkby 2004).

Conclusions

The agricultural sector is under pressure to respond to land degradation and associated soil fertility decline. The study investigated the impact of *Acacia decurrens* plantation, and charcoal production on soil properties and the community's livelihood in acidic soils of tropical agroecosystems. The finding of this research indicates that integration of *A. decurrens* in the farming system along with charcoal production transformed the landuse towards agroforestry systems, with positive contribution to land restoration and diversifying livelihood options while improving household income.

The implication of the findings of this study is a win–win situation of restoring landscapes and financial gains to farmers due to integration of *A. decurrens.* Most of the soil properties investigated in this study were positively influenced by *Acacia decurrens* plantation. Overall, the expansion of *A. decurrens* plantation has improved community's livelihood and natural resource base, particularly amelioration of soil acidity. However, further research is needed on the long-term effects of the *A. decurrens* based farming upon repeated rotation on the benefits of soil ecosystems. Research is also required to evaluate the residual effects of charcoal as soil amendments on soil biophysical and chemical properties and carbon sequestration on charcoal production areas under field conditions.

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