Sustainability **2015**, *7*, 2322-2337; doi:10.3390/su7032322

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Soil Quality Indices for Evaluating Smallholder Agricultural Land Uses in Northern Ethiopia

Aweke M. Gelaw [1,*], B. R. Singh [2] and R. Lal [3]

[1] Ethiopian Agricultural Transformation Agency, P.O. Box 708, Off Meskel Flower Road across Commercial Graduates, Addis Ababa, Ethiopia

[2] Norwegian University of Life Sciences, P.O. Box 5003, 1432 Ås, Norway; E-Mail: balram.singh@nmbu.no

[3] Carbon Sequestration and Management Center, The Ohio State University, Columbus, OH 43210, USA; E-Mail: lal.1@osu.edu

* Author to whom correspondence should be addressed; E-Mail: awekegelaw@gmail.com; Tel.: +251-920803761.

Academic Editor: Douglas L. Karlen

Received: 12 January 2015 / Accepted: 15 February 2015 / Published: 27 February 2015

Abstract: Population growth and increasing resource demands in Ethiopia are stressing and degrading agricultural landscapes. Most Ethiopian soils are already exhausted by several decades of over exploitation and mismanagement. Since many agricultural sustainability issues are related to soil quality, its assessment is very important. We determined integrated soil quality indices (SQI) within the surface 0–15 cm depth increment for three agricultural land uses: rain fed cultivation (RF); agroforestry (AF) and irrigated crop production (IR). Each land use was replicated five times within a semi-arid watershed in eastern Tigray, Northern Ethiopia. Using the framework suggested by Karlen and Stott (1994); four soil functions regarding soil's ability to: (1) accommodate water entry (WE); (2) facilitate water movement and availability (WMA); (3) resist degradation (RD); and (4) supply nutrients for plant growth (PNS) were estimated for each land use. The result revealed that AF affected all soil quality functions positively more than the other land uses. Furthermore, the four soil quality functions were integrated into an overall SQI; and the values for the three land uses were in the order: 0.58 (AF) > 0.51 (IR) > 0.47 (RF). The dominant soil properties influencing the integrated SQI values were soil organic carbon (26.4%); water stable aggregation (20.0%); total porosity (16.0%); total nitrogen (11.2%); microbial biomass carbon (6.4%); and cation exchange capacity (6.4%). Collectively, those six indicators accounted for more than 80% of the overall SQI values.

Keywords: soil quality; soil functions; land degradation; land use; Ethiopia

1. Introduction

Land degradation and declining soil fertility are critical problems affecting agricultural productivity and human welfare in Sub-Saharan Africa [1]. The main soil-environmental concerns in the region are nutrient depletion, loss of soil organic matter (SOM) and loss of soil functions (*i.e.*, productivity) [1,2]. In Ethiopia, total cultivated land has reached ~12 million hectares in mid-2013, but most of the soils are highly degraded [3]. Further, population growth and agricultural production are not growing *at par*. As a result, expansion to marginal lands and protected areas has become a common practice.

Tigray, the northernmost region in Ethiopia, is most known for its serious land degradation problems. Much of the woodland in Tigray started to disappear in the early 1960s under pressure from the rapidly growing population [4]. Hengsdijk *et al.* [5] wrote their observations as follows: "perhaps nowhere in the world land degradation and soil nutrient depletion are more evident than in the marginal highlands of Tigray". In the region, a short and variable rainy season in combination with degraded soils resulted in low soil productivity and frequent crop failures. As a result, the local population is structurally dependent on food aid [6]. If unattended to, land degradation and soil nutrient depletion would further reduce agricultural productivity and increase pressure on marginal environments, adversely affecting food security and livelihoods of smallholder farmers in the region [6].

Indeed, Tigray is not only known for its severe land degradation, but also for its vast environmental rehabilitation efforts in the last two decades [7]. Among the recent efforts towards enhancing agricultural development in the region, rainwater harvesting has been widely adopted [8] because supplementary irrigation is essential for crop production in arid regions as it increases soil water availability during dry spells [9]. Further, farmers in Tigray have a culture of selectively taking care of trees, which are remnants of the original woodlands. *Acacia albida* Del. (Syn. *Faiderbhia albida* (Del.) A Chev.) trees are among the most selected ones in the region. Nowadays, farmers grow these trees in and around their farmlands in order to improve soil fertility and increase crop yields [10].

Sustainability of agricultural systems is an important issue in Ethiopia. Many of the issues of agricultural sustainability are related to soil quality. Thus, its assessment and the direction of change with time is a primary indicator of whether agriculture is sustainable [11,12]. Soil quality is a combination of soil physical, chemical and biological properties that are able to change readily in response to variations in soil conditions [13]. It may be affected by land use type and agricultural management practices because these may cause alterations in soil's physical, chemical and biological properties, which in turn results in change in land productivity [14,15]. Integrated soil quality indices based on a combination of soil properties provide a better indication of soil quality than individual parameters. Karlen and Stott [16] developed a soil quality index (SQI) based on four soil functions, namely the ability of the soil to: (1) accommodate water entry (WE); (2) facilitate water movement, and absorption (WMA); (3) resist surface degradation (RD); and (4) supply nutrients for plant growth (PNS). Each soil function was explained by a set of indicators. Several authors among them Glover *et al.* [17], Masto *et al.* [12] and Fernandes *et al.* [18] used a similar framework.

A soil quality index (SQI) helps to assess the soil quality of a given site or ecosystem and enables comparisons between conditions at plot, field or watershed level under different land uses and management practices. Several studies were conducted to assess fertility statuses of soils in SSA [1–8]; however, almost all were only based on evaluation of individual soil parameters. Therefore, this study was conducted at a typical semi-arid agricultural watershed in Eastern Tigray, Northern Ethiopia, with the following objectives:

(1) To evaluate effects of *F. albida* based agroforestry (AF), irrigation based *Psidium guajava* fruit production (IR) and a tree-less row-crop management (RF) (Figure 1) on selected physical, chemical and biological soil quality indicators and,
(2) To compute an overall integrated soil quality index (SQI) for each land use system and compare among the indices.

Figure 1. The three agricultural land use systems at a semi-arid watershed in Tigray, Northern Ethiopia, with dryland crop production (RF), *F. albida*-based agroforestry (AF) and irrigation-based *P. guajava* fruit production (IR).

The study was conducted to test the hypothesis that land use change from dry land rainfed cultivation (RF) to *F. albida* agroforestry (AF) and irrigation based *P. guajava* fruit production (IR) systems improves physical, chemical, and biological soil quality indicators and the overall integrated soil quality index.

2. Materials and Methods

2.1. Descriptions of the Study Site

Mandae watershed is located in Eastern Tigray, Northern Ethiopia. Geographically, it is located between 15°26′00N to 15°32′00N latitude and 55°00′00E to 55°60′00E longitude, with an area of about 10 km^2, and an elevation of 1960 to 2000 m a.s.l. Average daily air temperature of the area ranges between 15 °C and 30 °C in winter and summer, respectively. Mean annual rainfall of the area is 558 mm, with a large inter-annual variation. Soils are classified as Arenosols, and associations of Arenosols with Regosols according to the World Reference Base for soil resources [19]. These soils are developed from alluvial deposits and Adigrat sandstones. Their textures are dominated by sand, loamy sand and sandy loam fractions [20]. Major land uses of the watershed include *Faidherbia albida* based agroforestry (27.7 ha), rainfed crop production (11.9 ha), open pasture (23.2 ha), and irrigation-based guava (*P. guajava)* fruit production (11.3 ha). Agricultural rotation in the area is usually maize (*Zea mays*)-teff (*Eragrostis tef*)-field beans (*Vicia faba*)-finger millet (*Eleusine coracana*) in the agroforestry and rainfed cultivation land use systems. Fallowing is not practiced in the area due to population pressure and scarcity of farmlands. Use of chemical fertilizers is minimal and land is prepared for cultivation by using a wooden plow with oxen. Crop residues and manures are used for animal feed and household fuel, respectively. No pesticides and other agricultural inputs are used in the area. Irrigation from shallow wells started in the area in late 1990s and currently most of the irrigated areas are covered by guava fruits. Smallholder mixed crop-livestock farming is a typical farming system of the region.

2.2. Soil Sampling and Analysis

Fifteen soil samples were collected in May 2010 from the surface (0–15 cm) layer of five sites randomly chosen at different locations from three agricultural land uses (AF, IR and RF). The summit position of the watershed was excluded to minimize confounding effects of slope and soil erosion. The samples were air-dried, mixed, ground, and passed through a 2-mm sieve for chemical analyses. Core samples were also collected from the same depth using 100 cm^3 volume stainless steel tubes (5-cm diameter and 5.1-cm height). Initial weights of the soil cores were measured in the laboratory immediately after collection. Simultaneously, soil moisture content was determined gravimetrically by oven drying the whole soil at 105 °C for 24 h to compute dry bulk density (ρ_b) [21]. No adjustment was made for rock volume because it was rather minimal. The major parts of the soil analyses were carried out at Mekelle University soil laboratory, Ethiopia. Soil organic carbon (SOC) and total nitrogen (TN) were analyzed at the Carbon Sequestration and Management Center (C-MASC) Laboratory (The Ohio State University, Columbus, OH, USA) using auto CN analyzer (Vario Max CN Macro Elemental Analyser, Elementar Analysensysteme GmbH, Hanau, Germany) by the dry combustion method [22]. Similarly, water stable aggregation (WSA) was measured at C-MASC soil physics laboratory by the wet sieving method [23]. Because soils did not show carbonates when tested with 10% HCl, it was assumed that the total C obtained in the analysis closely estimates soil organic carbon (SOC) concentration. Available P (Olsen) was analyzed using a standard Olsen method [24]. Cation exchangeable capacity (CEC) was estimated titrimetrically by ammonium distillation method [25]. Lastly, total porosity was calculated from particle density of 2.65 g/cm^3.

Microbial Biomass Carbon (MBC)

Another set of nine field-moist soil samples (40 g each) from the surface (0–15 cm) depth were collected in three replications from the three agricultural land uses (AF, IR and RF) in May 2012 for the determination of microbial biomass carbon (MBC). The samples were transported in an icebox to the Norwegian University of Life Sciences soil laboratory, Ås, Norway. The MBC analysis was carried out following the fumigation-extraction method [26,27]. At first, each sample was divided in to three subsamples, and one out of the three (10.0 g) was fumigated with ethanol-free chloroform for 24 h at 25 °C in an evacuated extractor. Afterwards, from the remaining two subsamples, one was used for moisture determination and the other treated as control for each plot. Fumigated and non-fumigated soils were extracted with 40-mL 0.5-mol·L^{-1} K_2SO_4 (1:4 soil:extractant) and shaken for 1-h on a reciprocal shaker. The extracts were filtered using Whatman No. 42 filter paper of 7-cm diameter and stored frozen at −15 °C prior to analysis. Finally, total organic carbon in the extracts was measured using Total Organic Carbon Analyzer (SHIMADZU) at NMBU laboratory, Ås, Norway. Microbial Biomass Carbon (MBC) was calculated as follows:

$$MBC = E_C / KE_C \tag{1}$$

where E_C = (organic C extracted from fumigated soils) − (organic C extracted from non-fumigated soils) and KE_C = 0.45 [28].

2.3. Soil Quality Assessment

Soil quality assessment tools need to be flexible in terms of selection of soil functions to be assessed and indicators to be measured to ensure that assessments are appropriate for specific management goals [29]. Effects of land use on soil quality were assessed following the framework suggested by Karlen and Stott [16]. We followed this framework because of its flexibility, ease of use and its potential for interactive use. It is the same approach that became the Soil Management Assessment Framework (SMAF) [30]. It uses selected soil functions, which are weighted and integrated according to the following expression:

$$SQI = WE(wt)+WMA(wt)+RD(wt)+PNS(wt) \tag{2}$$

where, wt is a numerical weighting for each soil function.

These numerical weights were assigned to each soil function according to their importance in fulfilling the overall goals of maintaining soil quality under specific conditions of this study. According to Karlen and Stott [16], the sum of weights for all soil functions must equal 1.0. Karlen and Stott [16] assigned equal weight to each soil function. However, different weight values of 0.2, 0.2, 0.2 and 0.4 were assigned for this study for WE, WMA, RD, and PNS, respectively (Table 1). For this study, PNS was assigned with more value than other functions, because use of chemical fertilizers was minimal in the area and hence nutrient supply was considered the most important production constraint. Further, sustaining crop production is the major goal of soil management strategies in most developing countries including Ethiopia. The PNS function was further divided into three second-level functions viz. nutrient storage, nutrient cycling and nutrient availability (Table 1).

Table 1. Soil quality indexing framework (adapted from Glover *et al.* [17]).

Function	Weight	Indicator Level 1	Weight	Indicator Level 2	Weight	Source for Indicators/Weights
Accommodate Water Entry	0.20	WSA	0.40			[17,31]
		BD	0.20			[17]
		POR	0.20			[12]
		SOC	0.20			[12]
Facilitate Water Movement and Availability	0.20	POR	0.60			[12,17,31]
		SOC	0.40			[17,31]
Resist Surface Degradation	0.20	WSA	0.60			[17,31]
		Microbial Processes	0.40	MBC	0.60	[12,17,31]
				SOC	0.20	[12,17,31]
				TN	0.20	[12;31]
Supply Plant Nutrient	0.40	Nutrient Storage	0.40	CEC	0.40	[12]
				SOC	0.40	[12]
				TN	0.20	[12]
		Nutrient Cycling	0.20	SOC	0.40	[12,31]
				MBC	0.20	[12,31]
				TN	0.40	[31]
		Nutrient Availability	0.40	SOC	0.20	[12]
				pH	0.20	[31]
				TN	0.20	[12]
				AVP	0.20	[12]
				AVK	0.20	[12]

An ideal soil would fulfill all the functions considered important, and would have an integrated SQI of 1.0 under the proposed framework. However, as a soil fails to meet the ideal criteria, its SQI would decrease, with zero being the lowest rating. Associated with each soil function are soil quality indicators that influence, to varying degrees, the specific soil function. Threshold values for each soil quality indicator were set based on the range of values measured in natural ecosystems (the adjacent grass pasture in our case) and on critical values in the literature (Table 2). Glover *et al.* [17] also used adjacent grass pasture areas to determine critical values for a study conducted in Washington State, USA. After finalizing the thresholds, the soil property values recorded under the three agricultural land use systems were transformed into unit-less scores (between 0 and 1), using the following equation [12]:

$$\text{Non-linear score(Y)} = \frac{1}{(1+e^{-b(x-A)})} \tag{3}$$

where, x is the soil property value, A the baseline or value of the soil property where the score equals 0.5 and b is the slope of the tangent to the curve at the baseline.

Table 2. Relative importance of the different soil properties used for the soil quality indexing.

Soil Quality Indicator	Weight	Soil Function
Soil organic carbon	0.264	Accommodate water entry Facilitate Water movement and availability Resist Surface structure degradation Supply plant nutrients
Aggregate Stability	0.200	Accommodate water entry Facilitate Water movement and availability Resist surface structure degradation
Bulk density	0.040	Accommodate water entry
Porosity	0.160	Accommodate water entry Facilitate water movement and availability
Microbial biomass carbon	0.064	Resist surface structure degradation Supply plant nutrients
Cation exchange capacity	0.064	Supply plant nutrients
Total Nitrogen	0.112	Supply plant nutrients Resist surface structure degradation
Available phosphorus	0.032	Supply plant nutrients
Available Potassium	0.032	Supply plant nutrients
pH	0.032	Supply plant nutrients
Total	1.00	

The score for each indicator was calculated after establishing the baseline, the lower, and the upper threshold values (Table 3). Threshold values are soil property values where the score equals one (upper threshold) when the measured soil property is at the most favorable level; or equals zero (lower threshold) when the soil property is at an unacceptable level. Baseline values are generally regarded as minimum target values [12]. There are two baselines for "Optimum" curves, lower base line and upper base line, which corresponds to 0.5 score of the growth and death curves, respectively [12].

Table 3. Scoring function values and references used for evaluating the soil quality indices (adapted from Masto *et al.* [12]).

Indicator	Scoring Curve	Depth (cm)	LT	UT	LB	UB	OPT	Slope	Source of Threshold/ Baseline Values
				Physical properties					
BD (Mgm^{-3})	Less is better	0–15 cm	1.0	2.0	1.5	-	-	−2.0832	[31]; Adjacent grass pasture
WSA (>0.5 mm)	More is better	0–10 cm	0.0	40.0	20.0	-	-	0.0339	Adjacent grass pasture
TP (V%)	Optimum	0–15 cm	20.0	80.0	40.0	60.0	50.0	0.0644	[12,31]; Adjacent grass pasture
				Chemical Properties					
CEC (cmol (+) kg^{-1})	More is better	0–15 cm	0.0	18.0	9.0	-	-	0.0757	[12]; Adjacent grass pasture

Table 3. *Cont.*

Indicator	Scoring Curve	Depth (cm)	LT	UT	LB	UB	OPT	Slope	Source of Threshold/ Baseline Values
pH (1:2.5)	Optimum	0–15 cm	3.0	9.0	5.0	8.0	7.0	0.5332; −0.496	[18]
TN (kgha^{-1})	More is better	0–15 cm	0.0	2000.0	1000.0	-	-	0.0007	[12]; Adjacent grass pasture
AVP (kgha^{-1})	More is better	0–15 cm	0.0	50.0	25.0	-	-	0.0226	[12]
AVK (kg·ha^{-1})	More is better	0–15 cm	0.0	400.0	200.0	-	-	0.0036	[12]
Biological Properties									
SOC (gkg^{-1})	More is better	0–15 cm	0.0	10.0	5.0	-	-	0.1341	[12]; Adjacent grass pasture
MBC (mgkg^{-1})	More is better	0–15 cm	0.0	300.0	150.0	-	-	0.0042	[12]; Adjacent grass pasture

Using this non-linear scoring curve equation, three types of standardized scoring functions typically used for soil quality assessments were generated: (1): More is better"; (2) "Less is better"; and (3) "Optimum" as per earlier studies [12,16–18,31,32]. The equation defines a "More is better" scoring curve for positive slopes, a "Less is better" curve for negative slopes, and an "Optimum" curve is defined by the combination of both positive and negative slopes. These scoring curves are presented in detail by many authors [17,18,31–34].

2.4. Statistical Analyses

Effects of different land use systems on soil quality indicators, functions and integrated quality indices were subjected to one-way ANOVA. Excel spreadsheet was used for transforming soil quality indicator values into unit-less scores. Differences between means of parameters were considered significant at the 0.05 level using the Tukey's studentized (HSD) test. The data were analyzed using R version 3.02 software package [35].

3. Results and Discussion

3.1. Soil Physical Quality Indicators

Bulk density ranged from 1.48 Mg·m^{-3} in AF to 1.57 Mg·m^{-3} in both IR and RF land use systems (Table 4). However, there was no significant difference in BD among land uses. Although soils under AF land use contained SOC concentration twice more than that under RF, the detrimental effects of tillage may have offset the beneficial effects of SOC on BD [17,32]. Soils under AF land use also had the highest percentage of water stable aggregates (WSA) of 17.3%, but it was not significantly higher than that under IR and RF land uses. Addition of more organic matter from leaf and root litters from the *F. albida* trees in AF than the other land uses likely explains the improved WSA in AF [36]. Similarly, a study by Gelaw *et al.* [37] at the same site found that soils under natural grazing lands adjacent to cultivated lands were well structured, and contained higher SOC concentrations.

Total porosity (TP) ranged from 35.5% in RF to 43.5% and 44.9% in AF and IR land uses, respectively. However, the difference among land uses was not statistically significant. Similarly, the detrimental effects of tillage may have offset the beneficial effects of SOC on TP [17,32,37].

Table 4. Effects of land use systems on selected soil physical, chemical and biological quality indicators at Mandae watershed in eastern Tigray, north Ethiopia.

Soil Quality Indicator	Land Use			
	RF	AF	IR	
Physical				
BD ($Mg·m^{-3}$)	1.57 (0.03)	1.48 (0.05)	1.57 (0.02)	NS
WSA (>0.5 mm)	11.3 (1.8)	17.3 (2.5)	13.6 (3.6)	NS
TP (V%)	35.4 (3.6)	43.5 (2.0)	44.9 (2.7)	NS
Chemical				
CEC (cmol (p+) kg^{-1})	5.4 (1.0) ^{b}	11.5 (0.8) ^{a}	4.8 (1.8) ^{b}	**
pH	6.6 (0.3) ^{b}	6.4 (0.2) ^{b}	8.0 (0.03) ^{a}	***
TN ($kg·ha^{-1}$)	809.7 (134.6) ^{b}	1568.6 (85.4) ^{a}	1042.7 (244.6) ^{a,b}	*
AVP ($kg·ha^{-1}$)	24.4 (10.7)	39.1 (4.3)	39.8 (4.7)	NS
AVK ($kg·ha^{-1}$)	216.5 (56.9) ^{b}	1019.1 (161.0) ^{a}	297.7 (71.8) ^{b}	***
Biological				
SOC ($g·kg^{-1}$)	3.2 (0.7) ^{b}	6.4 (0.3) ^{a}	5.9 (1.1) ^{a,b}	*
MBC ($mg·kg^{-1}$)	75.5 (24.1)	95.9 (10.3)	100.1 (31.3)	NS

RF, Dryland crop production; AF, *Faidherbia albida* based agroforestry; IR, irrigation based fruit production; ± Mean values followed by standard errors in the parentheses; values with different letters are significantly different.* $p < 0.05$; ** $p < 0.01$; NS = not significant (Tukey's test, $p = 0.05$).

3.2. Soil Chemical Quality Indicators

CEC of the soils studied ranged from the highest under AF (11.5 cmol p+ kg^{-1}) to the lowest under IR (4.8 cmol p+ kg^{-1}). It was significantly higher ($p < 0.01$) under AF than that under IR and RF land uses (Table 4). Generally, CEC was low with an exception of some improvements under AF land use. Rabia *et al.* [20] also reported similar results for the same area. Accordingly, up to 90% of soil samples from this area had extremely-low (<5)-to-low (5–15 cmol p+ kg^{-1}) CEC values [20]. EC values of the soils were also much lower than the FAO salinity hazard levels for most crops [20] (Table 4).

In general, Arenosols have neutral pH values [38]. However, soils under IR land use showed a significantly higher ($p < 0.001$) pH value than that under other land uses, and it was slightly alkaline. The source of this slight alkalinity development in the soil under IR land use could be from the supplemental irrigation. Similar results were also reported by Rabia *et al.* [20].

Soils under AF contained the highest total nitrogen (TN) stock (1568.6 $kg·ha^{-1}$), and it was significantly higher ($p < 0.05$) than that in IR and RF land uses (Table 4). Hadgu *et al.* [10] reported similar results in their study in central Tigray, Northern Ethiopia, which compared TN contents of soils under canopies of *F. albida* and eucalyptus trees with those from tree-less fields. Similarly, available potassium (AVK) was significantly higher ($p < 0.001$) under AF than that under other land uses (Table 4). In contrast, available phosphorus (AVP) contents did not differ among land uses. The higher AVK under AF than that under other land uses could be related to the recycling of nutrients in the aboveground biomass, root biomass or through the recycling of depositions by cattle, which gather for shade under the tree-canopies during sunny days [39]. Sanchez [40] also reported a significant increase both in soil K content and sorghum (*Sorghum bicolar*) yield on soils under the canopy of *F. albida* trees from that on soils 15-m away in two parklands in Burkina Faso. Results presented here are also in accord with reports by Nair [41] that microsite enrichment qualities of trees such as *F. albida* in West Africa and *P. cineraria* in India have long been recognized in many traditional farming systems.

3.3. Soil Biological Quality Indicators

Both SOC and MBC are among principal soil parameters, which affect biological processes and soil quality. The highest SOC concentration was measured in AF (6.4 $g \cdot kg^{-1}$) followed by that in IR (5.9 $g \cdot kg^{-1}$), and the lowest was in RF (3.2 $g \cdot kg^{-1}$) (Table 4). Thus, SOC was significantly higher ($p < 0.05$) in AF than that in RF land use. However, it did not statistically differ between AF and IR, and between IR and RF land uses (Table 4). On the other hand, MBC was slightly higher in soils under IR (100.1 $mg \cdot kg^{-1}$) than that under AF and RF, but the differences were not statistically significant (Table 4). Higher MBC values under IR than that under AF and RF may be explained by less disturbance of soils under IR than those under the other intensively tilled land uses. The intensity of tillage in IR was less than that under AF and RF land uses. Besides, irrigation farms under guava fruits were not convenient for oxen plowing. Weed control and irrigation in IR land use were also practiced by hand. Soil organic carbon in intensively cultivated soils has less physical protection than that in less cultivated soils because tillage disrupts macroaggregates and exposes previously protected SOM microbial processes [14,37]. Similarly, Franchini *et al.* [42] reported an increase in MBC under no-till (NT) than that under conventional tillage systems (CT) receiving more plant residues in Southern Brazil. The lower MBC regardless of more plant residue addition under CT was due to higher CO_2-emissions, which implies little conversion of carbon from plant residues into MBC [42]. Indeed, parameters associated with soil microbiological activities are sensitive, considered rapid indicators of effects of soil management, and are useful as indicators of soil quality [42].

3.4. Soil Quality Indicators Integration and Assessment

For this study, four soil functions contributed to the overall soil quality index (SQI) (Table 1). They were weighted according to their relative importance in fulfilling the goals of maintaining soil quality in the area. Thus, the major driving soil parameters for the integrated SQI were SOC (26.4%), WSA (20.0%), TP (16.0%), TN (11.2%), MBC (6.4%) and CEC (6.4%). Those six soil quality indicators together contributed for more than 80% of the variability in the overall SQI (Table 2). Further, BD contributed 4.0% followed by AVP, AVK and pH with a contribution of each 3.2% to the overall SQI. Regarding the soil's function for plant nutrient supply, SOC, TN, and CEC contributed 32%, 24%, and 16% of the PNS function, respectively. Available P, AVK and pH each contributed 8% of the soil's function for plant nutrient supply. The soil's MBC contribution to this function was minimal (4%). Overall, SOC alone contributed for more than 25% and 30% of SQI and PNS values, respectively.

Integration of the soil property values into SQI using the framework resulted in a significantly higher ($p < 0.05$) score in AF than in RF land use system for its ability to accommodate water entry (Table 5). The relatively higher WSA, TP and SOC values of the soil under AF land use than those in the soil under RF were largely responsible for the improvement in its ability to accommodate water entry in AF (Table 4). Glover *et al.* [17] also reported higher scores for soil's ability to accommodate water entry because of higher WSA and lower BD under integrated and organic management systems than those under a conventional system in Washington State, USA. Regarding the soil's ability to facilitate water movement and availability, AF also scored significantly higher ($p < 0.05$) value than RF because of the relatively higher TP and SOC values in AF (Table 5). These results indicated that AF land use improved the soil's ability to hold and release water mainly due to its higher SOC content (Table 4). However, land use had no significant effect on soil's resistance to surface degradation (Table 5). This may be a clear indication of the detrimental effects of tillage on soil structure [17,32,37]. In contrast, AF scored significantly higher ($p < 0.05$) value for the soil's ability to supply plant nutrients than RF largely due to higher levels of AVK, CEC, SOC, TN and AVP in the rooting zones of AF land use (Table 5). The score for the soil under IR land use was not significantly different from that under RF (Table 5). Further, the score for nutrient storage capacity of soils under AF land use was significantly higher ($p < 0.05$) than that under RF, but it was not significantly different from that under IR (Figure 2). However, nutrient cycling was not significantly affected by land use regardless of some improvements in AF. Trees in agroforestry systems can improve nutrient cycling and increase soil chemical fertility through bringing up nutrients from deeper layers and minimizing leaching hazards [41]. In contrast, nutrient availability was affected by land use. Thus, AF scored significantly higher ($p < 0.01$) value for its capacity in nutrient availability than that in other land uses (Figure 2).

Table 5. Soil quality ratings for the different land uses at the watershed.

Soil Function	Land Use			
	RF	AF	IR	
Accommodate Water Entry (0.20)	0.09 (0.00) ^{b}	0.11 (0.002) ^{a}	0.10 (0.004) ^{a,b}	*
Facilitate Water Entry and Availability (0.20)	0.10 (0.004) ^{b}	0.12 (0.004) ^{a}	0.11 (0.004) ^{a,b}	*
Resist Surface Degradation (0.20)	0.09 (0.003)	0.11 (0.002)	0.09 (0.005)	NS
Source of Plant Nutrients (0.40)	0.19 (0.01) ^{b}	0.24 (0.004) ^{a}	0.21 (0.015) ^{a,b}	*
Integrated Soil Quality Index (1.00)	0.47 (0.01) ^{b}	0.58 (0.01) ^{a}	0.51 (0.02) ^{a,b}	**

RF, Dryland crop production; AF, *Faidherbia albida* based agroforestry; IR, irrigation based fruit production; ± Mean values followed by standard errors in the parentheses; values with different letters are significantly different. * $p < 0.05$; ** $p < 0.01$; NS = not significant (Tukey's test, $p = 0.05$).

Finally, the integrated SQI calculated for the land uses using the framework by Karlen and Stott [16] were in the following order: 0.58 (AF) > 0.51 (IR) > 0.47 (RF) (Table 5). Soil quality index differed significantly ($p < 0.01$) between AF and RF land use systems (Table 5). Similarly, Karlen *et al.* [31] reported an improvement in soil quality rating from 0.45 to 0.86 in over ten-year period by retention or addition of crop residues on a no-till (NT) continuous corn in Wisconsin, USA. In another study, Karlen *et al.* [32] reported a significant improvement in SQI ratings from 0.48 and 0.49 under plow and chisel, respectively, to 0.68 under NT using selected physical, chemical and biological soil quality indicators on Rozetta and Palsgrove silt loam soils in Wisconsin, USA. Stott *et al.* [43] in a recent study on Vertisols in Texas using the SMAF model also reported an improvement in overall SQI ranging from 75% to 94% of an optimum when compared with similar soils after 57 years of different agricultural management systems.

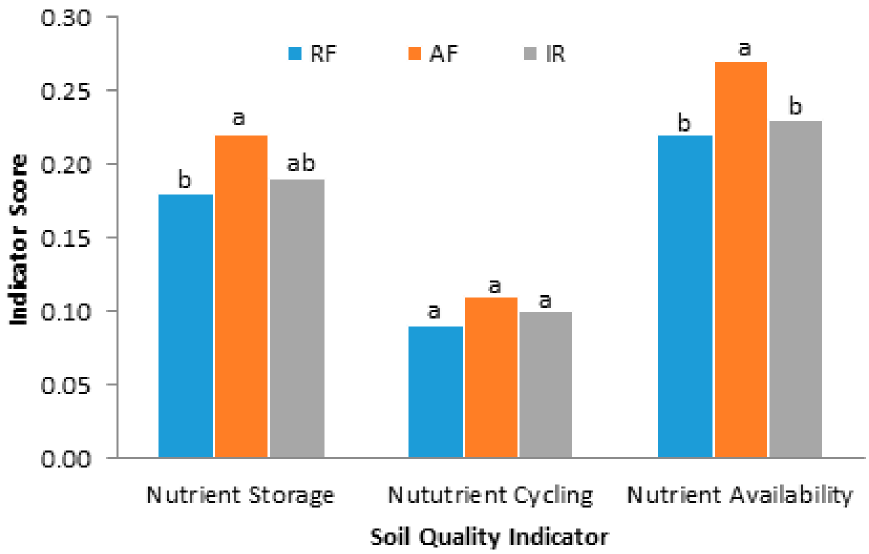

Figure 2. Effects of three agricultural land use systems (RF, AF and IR) on nutrient supplying capacities of soils at the watershed.

Regardless of a significant improvement in AF than that in RF land use, SQI ratings in all the three land use systems were very small compared with an ideal soil (Table 5). This result was in agreement with findings from other authors [5,44] who reported that low organic matter and nutrient stocks are typical characteristics of soils in Tigray, mainly due to nutrient mining because of crop harvests and complete removal of crop residues for feed and fuel. One fundamental principle of sustainability is to return to the soil the nutrients removed through harvests and other loss pathways [45], and one of the main tenets of agroforestry is that trees enhance soil fertility [45,46]. This is supported by observations of higher crop yields near *F. albida* tree canopies in Ethiopia [10,47–49] and elsewhere [50,51], which showed the potentials of agroforestry systems in improving soil quality and productivity of smallholder farms in Ethiopia and the wider region.

4. Conclusions

Relatively higher WSA, TN and SOC concentrations measured in soils under AF land use resulted in improved water entry, movement and availability than those under IR and RF. Soil's ability to supplying plant nutrients was also improved under AF than under RF land use largely due to higher levels of AVK, CEC, SOC, TN and AVP in the rooting zones of AF land use. However, there was no significant improvement in the soil's resistance to surface degradation in all land uses, which may be because of the detrimental effects of tillage. Further, when selected physical, chemical, and biological soil quality indicators were integrated into an overall SQI, AF land use received a higher soil quality rating (0.58) than that of RF (0.47). Thus, the result of this study highlighted the potentials of *F. albida* based AF systems for improving soil quality and productivity of smallholder farms in the area. Further, it demonstrated the effectiveness of the soil quality indexing framework in the study area and beyond to assess soil quality and thus recognized that changes in soil and crop management are needed for a more efficient and sustainable use of soil resources.

Acknowledgments

The International Foundation for Science (IFS) (Grant No. C/4687) provided financial support for the fieldwork. Some laboratory facilities were provided by Mekelle University, Ethiopia. Practical laboratory work for WSA, SOC and TN determination was performed at the laboratory facility of the Carbon Management and Sequestration Center (C-MASC), at The Ohio State University (OSU), Columbus, OH, USA. Financial assistance from the Norwegian State Education Loan Fund for the first author is gratefully acknowledged. The department of Environmental Science (IMV), Norwegian University of Life Sciences (NMBU) is also acknowledged for paying the publishing fee.

Author Contributions

Aweke M. Gelaw: Conception of the idea, designing the experiment, collecting and analyzing the data, and writing the article; Bal Ram Singh: Conception of the idea, Supervision and reviewing the article; Rattan Lal: Conception of the idea, supervision and reviewing the article.

Conflicts of Interest

There is no conflict of interest among the authors.

References

1. Sanchez, P.A.; Shepherd, K.D.; Soule, M.J.; Place, F.M.; Buresh, R.J.; Izac, A.M.N.; Mokwunye, A.U.; Kwesiga, F.R.; Ndiritu, C.G.; Woomer, P.L.; *et al*. Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital. In *Replenishing Soil Fertility in Africa*; Buresh, R.J., Sanchez, P.A., Calhoun, F., Eds.; SSSA and ICRAF: Madison, WI, USA, 1997; pp. 1–46.
2. Smaling, E. An Agroecological Framework for Integrating Nutrient Management, with Special Reference to Kenya. Ph.D. Thesis, Agricultural University of Wageningen, Wageningen, The Netherlands, 1993; p. 250.
3. Agricultural Transformation Agency (ATA). Status of soil resources in Ethiopia and priorities for sustainable management. In Proceedings of the Global Soil Partnership (GSP) for Eastern and Southern Africa Launching Workshop, Nairobi, Kenya, 25–27 March 2013.
4. Eweg, H.P.A.; van Lammeren, R.; Deurloo, H.; Woldu, Z. Analysing degradation and rehabilitation for sustainable land management in the highlands of Ethiopia. *Land Degrad. Dev*. **1998**, *9*, 529–542.
5. Hengsdijk, H.; Meijerink, G.W.; Mosugu, M.E. Modeling the effect of three soil and water conservation practices in Tigray, Ethiopia. *Agric. Ecosyst. Environ*. **2005**, *105*, 29–40.
6. Belete, T. Efforts for Sustainable Land Management in Tigray: The role of Extension. In *Policies for Sustainable Land Management in the Highlands of Tigray, Northern Ethiopia*; Gebremedhin, B., Pender, J., Ehui, S., Haile, M., Eds.; International Food Policy Research Institute (IFPRI): Mekele, Ethiopia, 2002.

7. Girmay, G. Land Use Change Effects in Northern Ethiopia: Runoff, Soil and Nutrient Losses, Soil Quality, and Sediment as Nutrient Sources. PhD Thesis, Norwegian University of Life Sciences, Ås, Norway, 2009; p. 140.
8. Moges, G.; Hengsdijk, H.; Jansen, H.C. Review and quantitative assessment of *ex situ* household rainwater harvesting systems in Ethiopia. *Agric. Water Manag*. **2011**, *98*, 1215–1227.
9. Feng, Z.; Wang, X.; Feng, Z. Soil N and Salinity leaching after the autumn irrigation and its impact on ground water in Hetao irrigation district, China. *Agric. Water Manag*. **2005**, *71*, 131–143.
10. Hadgu, K.M.; Kooistra, L.; Rossing, W.A.H.; van Bruggen, A.H.C. Assessing the effect of Faidherbia albida based land use systems on barley yield at field and regional scale in the highlands of Tigray, Northern Ethiopia. *Food Secur*. **2008**, *1*, 337–350.
11. Karlen, D.L.; Mausbach, J.W.; Doran, J.W.; Cline, R.G.; Harris, R.F.; Schuman, G.E. Soil quality: A concept, definition and framework for evaluation. *Soil Sci. Soc. Am. J.* **1997**, *61*, 4–10.
12. Masto, R.E.; Chhonkar, P.K.; Singh, D.; Patra, A.K. Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol. *Agric. Ecosyst. Environ*. **2007**, *118*, 130–142.
13. Brejda, J.J.; Moorman, T.B.; Karlen, D.L.; Dao, T.H. Identification of regional soil quality factors and indicators: I. Central and southern high plains. *Soil Sci. Soc. Am. J.* **2000**, *64*, 2115–2124.
14. Islam, K.R.; Weil, R.R. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. *Agric. Ecosyst. Environ*. **2000**, *79*, 9–16.
15. Sanchez-Maranon, M.; Soriano, M.; Delgado, G.; Delgado, R. Soil quality in Mediterranean mountain environments: Effects of land use change. *Soil Sci. Soc. Am. J.* **2002**, *66*, 948–958.
16. Karlen, D.L.; Stott, D.E. A framework for evaluating physical and chemical indicators of soil quality. In *Defining Soil Quality for a Sustainable Environment*; Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A., Eds.; ASA and SSSA: Madison, WI, USA, 1994; pp. 53–72.
17. Glover, J.D.; Reganold, J.P.; Andrews, P.K. Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington State. *Agric. Ecosyst. Environ.* **2000**, *80*, 29–45.
18. Fernandes, J.C.; Gamero, C.A.; Rodrigues, J.G.L.; Mirás-Avalos, J.M. Determination of the quality index of a Paleudult under sunflower culture and different management systems. *Soil Tillage Res.* **2011**, *112*, 167–174.
19. WRB; International Union of Soil Science Working Group. *World Soil Resources Reports No. 103*; FAO: Rome, Italy, 2006.
20. Rabia, A.H.; Afifi, R.R.; Gelaw, A.M.; Bianchi, S.; Figueredo, H.; Huong, T.L.; Lopez, A.A.; Mandala, S.D.; Matta, E.; Ronchi, M.; *et al.* Soil mapping and classification: A case study in the Tigray Region, Ethiopia. *JAEID* **2013**, *107*, 73–99.
21. Blake, G.R.; Hartge, K.H. Bulk density. In *Methods of Soil Analysis. Part 1*, 2nd ed.; Klute, A., Ed.; American Society of Agronomy—Soil Science Society of America: Madison, WI, USA, 1986; pp. 363–375.
22. Nelson, D.W.; Sommers, L.E. Total carbon, Organic carbon and Organic matter. In *Methods of Soil Analysis. Part 3*; Book Series 5; Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E., Eds.; SSSA: Madison, WI, USA, 1996; pp. 961–1010.

23. Yoder, R.E. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. *J. Am. Soc. Agron*. **1936**, *28*, 337–351.
24. Olsen, S.R.; Cole, C.V.; Watanabe, F.S.; Dean, L.A. *Estimation of Available Phosphorous in Soils by Extraction with Sodium Bicarbonate*; USDA: Washington, DC, USA, 1954.
25. Chapman, H.D. Cation exchange capacity. In *Methods of Soil Analysis*; Black, C.A., Evans, D.D., Ensminger, L.E., White, J.L., Clark, F.E., Eds.; American Society of Agronomy: Madison, WI, USA, 1965; Volume 9, pp. 891–901.
26. Brookes, P.C.; Landman, A.; Pruden, G. Chloroform fumigation and release of soil N: A rapid direct extraction method to measure microbial biomass N in soil. *Soil Biol. Biochem*. **1985**, *17*, 837–842.
27. Vance, E.D.; Brookes, P.C.; Jenkinson, D.S. An extraction method for measuring soil microbial biomass C. *Soil Biol. Biochem*. **1987**, *19*, 703–707.
28. Wu, J.; Joergensen, R.G.; Pommerening, B.; Chaussod, R.; Brookes, P.C. Measurement of soil microbial biomass Carbon by fumigation-extraction an automated procedure. *Soil Biol. Biochem*. **1990**, *22*, 1167–1169.
29. Wienhold, B.J.; Karlen, D.L.; Andrews, S.S.; Stott, D.E. Protocol for Soil Management Assessment Framework (SMAF) soil indicator scoring curve development. Renew. *Agric. Food Syst.* **2009**, *24*, 260–266.
30. Andrews, S.S.; Karlen, D.L.; Cambardella, C.A. The soil management assessment framework: A quantitative soil quality evaluation method. *Soil Sci. Soc. Am. J.* **2004**, *68*, 1945–1962.
31. Karlen, D.L.; Wollenhaupt, N.C.; Erbach, D.C.; Berry, E.C.; Swan, J.B.; Eash, N.S.; Jordahl, J.L. Residue effects on soil quality following 10-years of no-till corn. *Soil Tillage Res*. **1994**, *31*, 149–167.
32. Karlen, D.L.; Wollenhaupt, N.C.; Erbach, D.C.; Berry, E.C.; Swan, J.B.; Eash, N.S.; Jordahl, J.L. Long-term tillage effects on soil quality. *Soil Tillage Res*. **1994**, *32*, 313–327.
33. Wymore, A.W. Model-Based Systems Engineering. In *An Introduction to the Mathematical Theory of Discrete Systems and to the Tricotyledon Theory of System Design*; CRC: Boca Raton, FL, USA, 1993.
34. Hussain, I.; Olson, K.R.; Wander, M.M.; Karlen, D.L. Adaptation of soil quality indices and application to three tillage systems in southern Illinois. *Soil Tillage Res*. **1999**, *50*, 237–249.
35. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna, Austria, 2012. Available online: http://www.R-project.org. (Accessed on 9 March 2014).
36. Tisdale, J.M.; Oades, J.M. Organic matter and water stable aggregates in soils. *J. Soil Sci*. **1982**, *33*, 141–161.
37. Gelaw, A.M.; Singh, B.R.; Lal, R. Organic carbon and nitrogen associated with soil aggregates and particle sizes under different land uses in Tigray, Northern Ethiopia. *Land Degrad. Dev*. **2013**, doi:10.1002/ldr.2261.
38. Hartemink, A.E.; Huting, J. Land Cover, Extent, and Properties of Arenosols in Southern Africa. *Arid Land Res*. *Manag.* **2008**, *22*, 134–147.

39. Arevalo, L.A.; Alegre, J.C.; Bandy, D.E.; Szott, L.T. The effect of cattle grazing on soil physical and chemical properties in a silvopastoral system in the Peruvian Amazon. *Agrofor. Syst*. **1998**, *40*, 109–124.
40. Sanchez, P.A. Science in agroforestry. *Agrofor. Syst*. **1995**, *30*, 5–55.
41. Nair, P.K.R. *An Introduction to Agroforestry*; Kluwer Academic Publishers: London, UK, 1993; p. 489.
42. Franchini, J.C.; Crispino, C.C.; Souza, R.A.; Torres, E.; Hungria, M. Microbiological parameters as indicators of soil quality under various soil management and crop rotation systems in southern Brazil. *Soil Tillage Res*. **2007**, *92*, 18–29.
43. Stott, D.E.; Cambardella, C.A.; Karlen, D.L.; Harmel, R.D. A Soil Quality and Metabolic Activity Assessment after Fifty-Seven Years of Agricultural Management. *Soil Sci. Soc. Am. J.* **2013**, *77*, 903–913.
44. Girmay, G.; Singh, B.R.; Mitiku, H.; Borresen, T.; Lal, R. Carbon Stocks in Ethiopian Soils in Relation to Land Use and Soil Management. *Land Degrad. Dev*. **2008**, *19*, 351–367.
45. Sanchez, P.A. Tropical soil fertility research, towards the second paradigm. *Transactions 15th World Congress of Soil Science*; International Society of Soil Science and Mexican Society of Soil Science: Acapulco, Mexico, 1994; Volume 1, pp. 65–88.
46. Palm, C.A. Contribution of agroforestry trees to nutrient requirements of intercropped plants. *Agrofor. Syst*. **1995**, *30*, 105–124.
47. Poschen, P. An evaluation of the Acacia albida-based agroforestry practices in the Hararghe highlands of Eastern Ethiopia. *Agrofor. Syst*. **1986**, *4*, 129–143.
48. Kamara, C.S.; Haque, I. Faidherbia albida and its effects on Ethiopian highland Vertisols. *Agrofor. Syst*. **1992**, *18*, 17–29.
49. Asfaw, Z.; Ågren, G.I. Farmers' local knowledge and topsoil properties of agroforestry practices in Sidama, Southern Ethiopia. *Agrofor. Syst*. **2007**, *71*, 35–48.
50. Kwesiga, F.; Coe, R. The effect of short-rotation Sesbania sesban planted fallows on maize yields. *For. Ecol. Manag*. **1994**, *64*, 199–208.
51. Sanchez, P.A.; Palm, C.A. Nutrient cycling and agroforestry in Africa. *Unasylva* **1996**, *47*, 24–28.