Original Paper

Understanding the Impact of Land Use and Land Cover Change on Water–Energy–Food Nexus in the Gidabo Watershed, East African Rift Valley

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Land use and land cover (LULC) changes have significant influences on the water–energy–food (WEF) nexus, as the WEF nexus characteristics change naturally due to dynamic LULC changes. However, understanding the WEF nexus' potential and characteristics in the watershed under the influence of LULC changes is less commonly explored. This study used the social network analysis (SNA) model to analyze the interaction between land use (LU) types and water, energy, and food nexus attributes. Moreover, we used regression analysis to analyze the impact of various LU types on the WEF nexus. The LULC maps of 1986, 2000, 2011, and 2019 were prepared by digital classification method with proper accuracy using satellite imagery. The results show that agroforestry is the dominant LU type, accounting for 25.8–53.1% from 1986 to 2019. Further, settlement increased a 100-fold, which shows the dynamic LULC changes. SNA computed the maximum inter-linkage for forest and water access attributes, while agroforestry and food attributes acted as bridge in the network. This shows that there was inter-dependence between LULC changes and the WEF nexus. This result suggests that LU dynamics can exert pressure on the WEF nexus' resource potential, resulting in WEF insecurity. The analysis of impacts of LULC changes on the WEF nexus shows that the changes that occurred in major LUs (i.e., agroforestry, bare land, settlements, and grass land) had significantly impacted hydrological behaviors, energy characteristics, and food production potential. Understanding LULC changes helps us to conserve and manage WEF nexus resources and to resolve the current dilemmas between land, water, energy, and food sector policies and decisions to improve resource productivity, lower environmental pressure, and enhance human wellbeing and security.

KEY WORDS: Land use and land cover change, Water–energy–food nexus, Interactive dynamic, Social network analysis, Agroforestry, Watershed level.

INTRODUCTION

The water–energy–food (WEF) nexus was introduced following the meeting of the World Economic Forum in 2011 (Hoff 2011b; Waughray 2011), and it relates to the growing demands associated with population growth, economic growth, urbanization, and environmental change (Karlberg et al. 2015; Kurian 2017). These demands put pres-

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sure on land cover (LC) change, which leads to ecological deterioration, thereby affecting the WEF nexus (Mohtar and Lawford 2016). The inclusion of land use (LU) as part of the WEF nexus to combat the significant challenges and intrinsic trade-offs that arise between WEF management systems is vitally important (Gulati et al. 2013; Leese and Meisch 2015). Indeed, land use and land cover (LULC) changes affect the supply and management of water, energy, and food resources (Nerini et al. 2018).

Previous studies revealed that there is strong interest in determining how LU change and water, energy, food resources interact each with other (Ringler et al. 2013; Karlberg et al. 2015). For example, farmland is a water and energy intensive process (Rasul 2014; Weitz et al. 2014), and there are also LU competitions between food crops and energy crops (Krasuska et al. 2010; Searchinger and Heimlich 2015). This highlights the link between nexus resources and specific LU systems. The decision to meet both human needs and nature conservation targets is subjected to the demand and supply of water, energy, and food (WEF) and can be determined by the nexus approach (Mehta et al. 2013; Ringler et al. 2013). However, nexus analyses performed only based on food demand aspects are a growing challenge (Pfister et al. 2011; Pahl-Wostl 2017); these challenges are linked with long-term LULC changes (Spera et al. 2016; Chen et al. 2018; Sušnik et al. 2018). In general, the literature indicates the increasingly independent management of land, water, energy, and food nexus resources (Ringler et al. 2013; Lee et al. 2018; Chen et al. 2018; Laspidou et al. 2019). However, managing interlinked resources separately or independently results in structural disruption, which leads to loss of the unique landscape and WEF nexus resources (Gulati et al. 2013; Chen et al. 2018). Such a loss is driven by the complex interactions of socio-economic, political, technological, natural, and cultural factors (Chen et al. 2018; Gessese 2018).

Although the idea of integrated natural resource management is old, the complex inter-relations among different resources are not yet well characterized, and more attention has been given to managing WEF nexus resources (Hoff 2011a; Leck et al. 2015). This limits the consideration of land as an essential nexus resource component for the survival, and prosperity of humanity and for the maintenance of all ecosystems (Chartres and Noble 2015; Gessese 2018), as well as the consideration of any

unintended effects of LULC changes that affect basic human resources i.e., WEF.

The challenges of LULC change will arise from long-term gradual changes, such as clearing of forests, loss of vegetation, expansion of built up land, and increased fuel wood and charcoal consumption, as well as from projected changes in population growth (Gessese 2018; Lee et al. 2018; Elias et al. 2019). The independent impacts of LULC changes on water, energy, and food have been studied extensively (Muriithi 2015; Calijuri et al. 2015; Suxiao Li et al. 2018). However, there are few analyses that capture the impact of LULC changes on the WEF nexus. To fill this gap, the current study evaluates the impact of LULC changes on the WEF nexus.

MATERIAL AND METHODS

Case Study Area

The Gidabo Watershed is part of the East African Rift that runs through Ethiopia in the southwest direction from the Afar Triple Junction (Grove 1986). This watershed is situated at latitudes 6° 9′ 4″ to 6° 56′ 4″ N and longitudes 37° 55′ to 38° 35″ E, covering an area ~ 3549 km^2 (Fig. 1). The maximum and minimum altitudes of the watershed are about 3213 and 1171 m.a.s.l., respectively.

The physiographic features of the watershed are mainly the results of faulting and volcanism associated with rifting processes (Yared 2019). In the southern rift area, where the Gidabo Watershed is located, the collapse of the rift takes place fairly regularly in a single block. As a result, the typical rift morphology is well developed in the area, and the three major physiographic regions of the, rift floor, escarpment, and highland are clearly visible and show the upper and lower parts of the watershed (Fig. 1).

Currently, the catchment's population is over 1.5 million (Meshesha et al. 2012), and the population increased by 33.3% in the last decades, as reported by the Ethiopia Central Statistical Agency (2010). Increased population in the basin and the socio-economic developments exert pressure on LULC changes and consequently result in declining water and food potential in the basin (Meshesha et al. 2012). Specifically, the population pressure on the land for settlements and farming has resulted in conversions of the previously dominant land-use
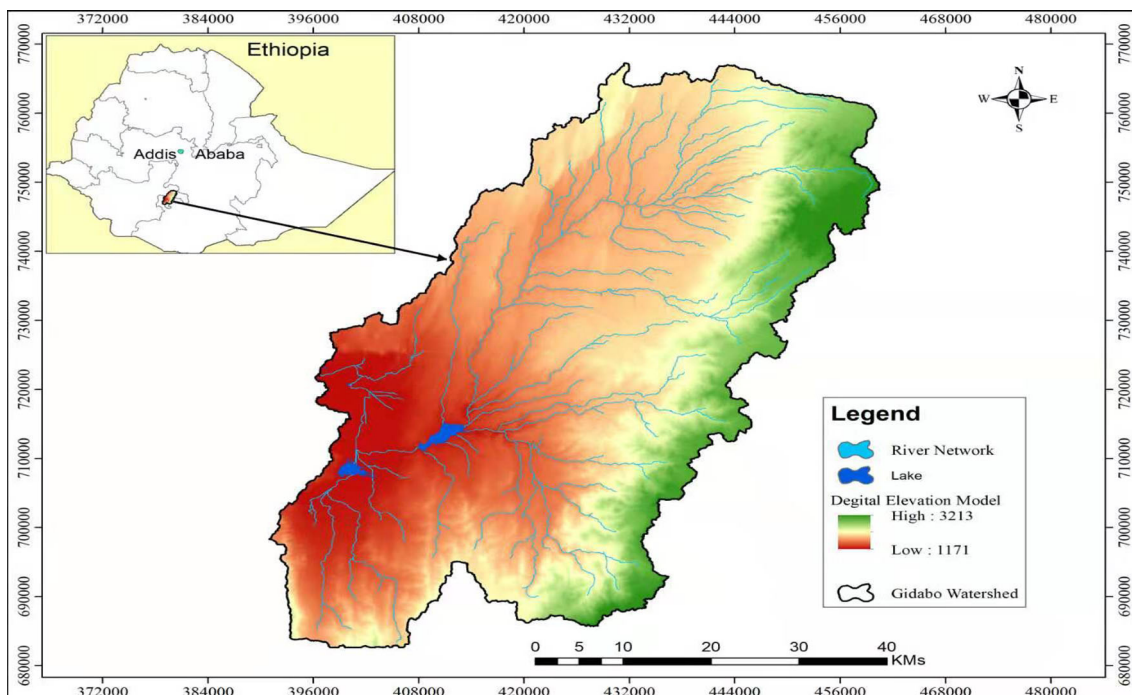
Figure 1. Map of the case study area.

types, of streams flows and lakes, as stated by Elias et al. (2019) and WoldeYohannes et al. (2018). This creates new demands for WEF resources.

Analyses of LULC Changes and the Water–Energy–Food Nexus System

To analyze the impact of LULC changes on the WEF nexus, we undertook two general steps: (1) LULC classification and change detection; (2) analysis of the relationships between LULC classes and the WEF nexus resources attributes.

To analyze LULC changes in the Gidabo Watershed, satellite data comprised multi-temporal satellite images from both Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) for four acquisition years (1986, 2000, 2011, and 2019) with less than 10% cloud cover were acquired. These acquisition years were selected to deliberately coincide with nationwide drought and famine in the 1980s, as well as government changes and subsequent policy and institutional structural changes of the county in the 1990s; moreover, the watershed campaign started in 2003 (Desta and Coppock 2002). The selected time variation has significant features

in Ethiopia. All satellite scenes used in this study were obtained from the website of the US Geological Survey (USGS, https://glovis.usds.gov/) (Table 1).

Each image was downloaded, and mosaics of the two scenes of p/r 168/56 and p/r 168/55 were made independently for each year. Then, band combination was performed. In addition to using high-resolution imagery, ancillary data were collected, including ground truth data, aerial photographs and topographic maps. The ground truth data were obtained in the form of reference data points collected using geographic positioning system (GPS) in the 2019 image analysis and used for image classification and accuracy assessments of the result.

To evaluate overall accuracy, the satellite data were imported into the ERDAS 2015 software in an image format for geometric correction, for which the images were geo-referenced, mosaicked, and subset based on the area of interest (AOI). All satellite data were studied by assigning per-pixel signatures and differentiating the land area into eight classes based on the specific digital number values of the landscape elements. Accuracy assessment using a confusion error matrix with Kappa coefficient, which is a common method. Based on this, an accuracy

Table 1. Remotely sensed data used in the analysis of LULC change

Sensor type	Path/row	No. of bands	Band combination	Spatial resolution (m)	Acquisition date
Landsat 5 (TM)	168/056	7	RGB 432	30	5/Jan/86
	168/055	7	RGB 432	30	1/18/1985
Landsat 5 (TM)	168/056	7	RGB 432	30	28/Jan/95
	168/055	7	RGB 432	30	28/Jan/00
Landsat 5 (TM)	168/056	7	RGB 432	30	10/Jan/11
	168/055	7	RGB 432	30	10/Jan/11
Landsat 8 (OLI)	168/056	11	RGB 543	15	31/Jan/19
	168/055	11	RGB 543	15	16/Jan/19

RGB Red–green–blue.

assessment was conducted for the years of 2000, 2011, and 2019, as there were no ground truth data or base maps for 1986. The Kappa coefficients obtained were 0.77, 0.73, and 0.80 for the 2000, 2011, and 2019 image respectively. The overall classification accuracy ranged from 77.5 to 83.5%.

LU classification standard and category confusion were determined based on the existing conditions of LU in the study area. The delineated classes were agroforestry, bare land, farmland, forest, grassland, settlement, shrub and woodland, and water body (Table 2). After following all the relevant steps and procedures, a satisfactory spectral signature was used to ensure minimal confusion among the land covers to be mapped. Finally supervised classification was performed by applying the maximum likelihood algorithm to the images. Post-classification refinement was used to reduce misclassification addressed by visual interpretation though local knowledge, reference data, and visual analysis. These steps considerably improved the results obtained using the supervised algorithm.

Post-classification change detection techniques were performed in ArcGIS 10 to detect location, nature, and rate of change. Another technique used to obtain the changes in LULC during the specified period was the overlay procedure. In this way, the two-way cross-matrix obtained by the application of this technique can be used to describe the key changes in the study area. Cross-tabulation analysis was conducted to determine the quantitative conversions from a particular category to another LC category and their corresponding area over the evaluated period on a pixel to pixel basis. Following Temesgen et al. (2018), the percentage of change within the same LULC change between two-time points was calculated as:

$$\Delta CL = \left(A_f - A_i / A_i\right) \times 100 \qquad (1)$$

where ΔCL is percentage change of LULC in relation to the initial year coverage, A_i is initial year area, and A_f is final year area. The annual rate of LULC changes was calculated as (Puyravaud 2003):

$$\Delta ARL = \left(1/t_2 - t_1\right) \ln\left(A_f / A_i\right) \qquad (2)$$

where ΔARL is annual rate of cover change, and t_2 and t_1 are the final and initial years.

To understand the intrinsic relationships between LULC and the WEF nexus, relevant data were collected from the local community using tally method. In total, 434 households were used to identify LU and WEF nexus attributes for the social network analysis (SNA). We used the SNA model to understand the bilateral linkage between LUs, water, energy, and food attributes, as explained by Bodin and Crona (2009) and Terrapon-Pfaff et al. (2018), using the *igraph package* in the R statistical software (Butts 2008).

SNA allows for the integration of water, energy, food, and land attributes in an analytical manner by mapping the key elements of the sub-system and visualizing their inter-dependencies. In this paper, we focused on computing the four most popular centrality measures used to map the inter-linkage between LU and WEF nexus attributes, as discussed by Otte and Rousseau (2002).

Density: This is the proportion of possible ties in a network that are actually present. *Density* is used to measure the extent to which all actors (i.e., LU and WEF attributes) in a network are tied to one another:

$$\text{density}(d) = \frac{n!}{(n-2)!} \qquad (3)$$

Table 2. Classes delineated on the basis of supervised classification

S/no	Class name	Descriptions
1	Agroforestry	Indigenously managed traditional tree, coffee, and *Enset*-based LU systems/ indigenous agro-silvo-pastoral system
2	Bare land	Land areas without vegetation and area of exposed soil
3	Farmland	Crop fields and fallow lands
4	Forest	Broad leaf tree with closed canopy
5	Grassland	Grass and herb cover with scattered trees and shrubs
6	Settlement	Residential, commercial, industrial, roads and mixed urban
7	Shrub and woodland	Woody Acacia plants stacked as a pack 5–20 m in height
8	Water body	River, open water, lakes, ponds and reservoirs

where n is number of nodes in the network and 2 is the maximum possible number of relationships between any two nodes in the network.

Degree centrality: This refers to how many others node nexus resource attributes are directly connected. This attributes shows the node with a high degree, and measures the number of links to and from an individual in a network. This attribute is computed as:

$$K = Ae \qquad (4)$$

where $A \in R^{n*n}$ is the adjacency matrix of an undirected graph, $K \in R^n$ is the *Degree* vector, and $e \in R^n$, is the all-one vector.

Closeness centrality: This indicates the peripherally of a node v, defined as the sum of its distances to all other nodes and a measure of how long nexus resources will take to interact from v to all other nodes sequentially. It is also called the inverse of farness, thus:

$$\text{Closeness}(v) = \frac{1}{\sum_i \neq v dvi} \qquad (5)$$

Betweenness centrality: The Betweenness of a vertex v in a graph $G:(V, E)$ with a pair of vertices (s, t) computes the shortest paths between the vertices, thus:

$$\text{Betweenness}(bv) = \sum_{s \neq v \neq t \in v}^{n} \frac{\delta st(v)}{\delta st} \qquad (6)$$

The next step was to analyze the impact of LULC changes on WEF nexus resources using the multiple regression model. This model was used to investigate the impact of LU classes over the entire period change (independent variable, $N = 8$) on the WEF

nexus resource variables as (dependent variable, $N = 8$). The WEF nexus variable data were obtained and manipulated from a document of the Central Rift Valley Basin (Seyoum et al. 2015). Finally, we used the mathematical equation of the regression model:

$$Nr_v = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon \qquad (7)$$

where Nr_v is the WEF nexus variable used as a continuous dependent variable, β_0 is the intercept, and $\beta_1,\ldots, \beta_n$ are the coefficients of the associated independent variables in our case, LU classes; ε is error.

RESULTS AND DISCUSSION

LULC Change

Based on the definition of LUs adopted from Ketema et al. (2020) and WoldeYohannes et al. (2018), we identified eight major LU classes: agroforestry, bare land, farmland, forest, grassland, settlement, shrub and woodland, and water body (Table 3). The result of the analysis over the study period (1986–2019) shows that agroforestry experienced the most increase, whereas shrub and woodland the most decrease (Fig. 2). We observed further a net positive change of 103% for agroforestry and a net decline of shrub and woodland by 61.8% (Table 3). Similarly, farmland decreased with overall areal variations of 297.58 km^2 with substantial loss of settlement, as ascertained by population growth. In the same period, the forest land shrank by 50%. Among the five LU classes showing an overall increase, the increase in water classes (0.36%) may be

Table 3. Classification results of LULC for the years 1986–2019

LULC types	LULC change								Areal variations (km²) 1986–2019	
	1986		2000		2011		2019			
	km²	%	km²	%	km²	%	km²	%	km²	%
Agroforestry	848.82	25.8	1295.06	39.4	1569.84	47.7	1745.94	53.1	+ 897.12	105.7
Bare land	4.65	0.10	21.20	0.60	24.65	0.70	28.5	0.90	+ 23.85	512.9
Farmland	700.26	21.3	617.9	18.8	538.63	16.4	402.68	12.2	− 297.58	− 42.5
Forest	337.99	10.3	210.27	6.40	211.82	6.40	169.03	5.1	− 168.96	− 50.0
Grassland	340.94	10.4	587.77	17.9	561.34	17.1	401.71	12.2	+ 60.77	17.8
Settlement	6.22	0.20	11.12	0.30	26.44	0.80	127.50	3.90	+ 121.28	1949.8
Shrub and Woodland	1048.56	31.9	543.51	16.5	352.22	10.7	400.14	12.2	− 648.42	− 61.8
Water	1.09	0.03	1.73	0.10	3.60	0.10	13.02	0.40	+ 11.93	1094.5
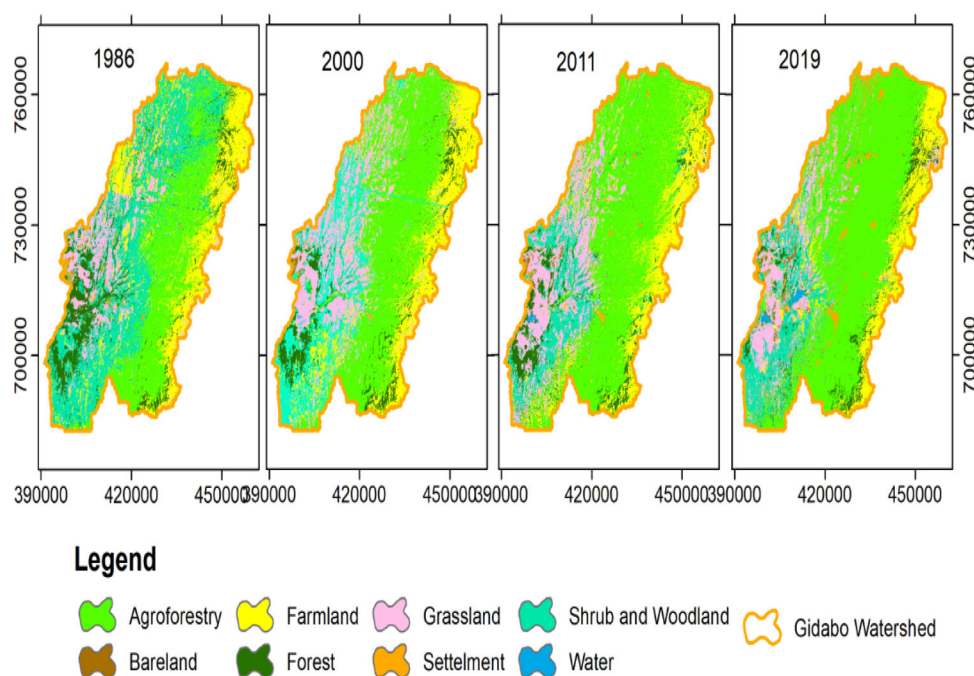
Figure 2. LULC change map of Gidabo Watershed, between 1986 and 2019.

due to many contributing streams joining together with the tributaries of the main rivers (Genet 2017).

Comparison of each LU class during 1986–2019 showed that there were marked LULC changes over the last 3 decades. Particularly, agroforestry LU increased within all year categories in the upper part of the watershed. This was due to increasing farming practices focusing on perennial crops, such as coffee, *Enset* (false banana), and *Chat* (*Catha edulis*), which drive the related economies as a major anthropogenic change of LU in the study area.

Farmland reduction over the whole study period (Table 3, Fig. 3) also indicated a shift from agricultural land to mixed agroforestry. According to Temesgen et al. (2018), the indigenous LU management featuring the intentional combination of agriculture and forestry offers various benefits, including increased biodiversity and reduced erosion.

Figure 2 indicates a slight increase in settlement and water body coverage, while forest decreased from 1986 to 2000. Interviews with local households
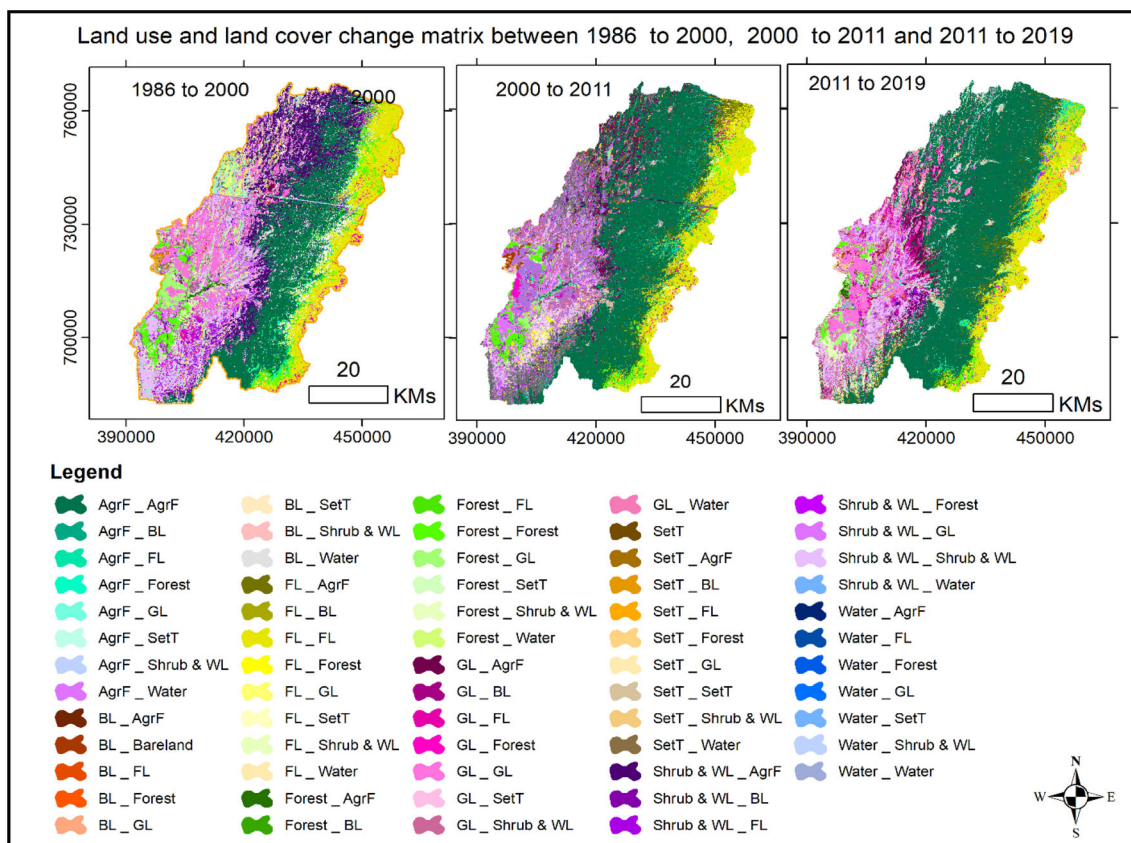
Figure 3. LULC change matrices for 1986–2000, 2000–2011, and 2011–2019.

revealed that settlement expansion was related to the dynamic increase in the population in the area, as reported by Abebe et al. (2006).

Forest decline was associated with rapid population growth and increasing demands for food and fuelwood. Hurni et al. (2010) also reported that in the years between 1990 and 2010, the total forest loss of Ethiopia was 18.6% due to unwise LU and farming systems caused by newly incoming informal settlers and land grabbing by former formal settlers. Additionally, during our field investigations, we observed that due to open access situations and the lack of locally binding rules, the large-scale cutting of trees and clearing of woodland from communal will represent a significant cause of LU change in the future.

Shrub and woodland was the dominant LU next to agroforestry, but a gradual decline in shrub and woodlands coverage at an annual rate of − 4.7% for the years 1986–2000 was observed. These characteristics are peculiar for the lower part of the

watershed, where LULC change poses risks to water sources due to a loss of the vegetation cover that acts as a barrier to the movement of material into the water system. The local community confirmed that a lack of fodder grass associated with water loss affected their livestock based livelihoods, which needs serious government intervention.

As outlined in the LULC change map for the year 2011–2019 (Fig. 2), the observed expansion of the built-up land and water bodies observed was associated with the expansion of the wet coffee processing industry in the study area. According to the Southern Ethiopia Bureau of Agriculture and Natural Resources in 2019, in the last 2 decades, a dynamic increase in wet coffee processing companies from 80 to 774 was observed. This increase was due to high land and water potential causing degradation of the land.

Table 3 indicates that bare land increased over the entire study period, which might be due to the clearing of grassland and the use of Acacia trees for

charcoaling and other uses. However, currently, there are large-scale efforts being mobilized to reclaim bare land and re-use it for agriculture. However, these substantial efforts remained below the maximum degradation extent. Following this, the new watershed campaign that started in 2011/2012 in the current study area was focusing on ecologically fragile and marginalized land that showed rehabilitation potential and real possibilities for restoring degraded areas in agreement with the findings of Temesgen et al. (2018).

Major LUCC Change Matrix

LU matrices are often used in LU studies to estimate quantitatively the rate of change of LUs. Based on the LU transfer matrices for the study region for 1986–2000, 2000–2011, and 2011–2019 (Fig. 3), all LULC categories experienced relative persistence during the study period. Additionally, the results obtained from the LULC change matrix map show major LC changes in the Gidabo Watershed (Fig. 3).

The change detection matrix highlighted changes that occurred between LULC classes during the study period (Table 4). Table 4 shows that 95.4% of the agroforestry persisted, while the remaining agroforestry was changed to forest (1.9%) and farmland (1.3%) between 1986 and 2019. However, agroforestry gained 64.7% and 23.4% coverage from shrub and woodland and farmland, respectively. This shows that farmers in the upper parts of the study area cultivated indigenous trees combined with other crops for a variety of benefits for their livelihoods and ecosystem services, which agrees with the findings of Kanshie (2002). Interviews with key informants together with focus group discussions showed that, from 1983 onwards, most of the forest was converted to shrub/grassland due to the demand of construction material, fuelwood, and charcoal highlighting the interconnection between land and energy.

The calculated percentages of cover classes showed that 46.6% of the mapping units of LU types remained unchanged during 1986–2019 (Table 4). Similarly, during this period, the LU transfer matrix occurred mainly between agroforestry, farmland, and shrub/woodland. Table 4 shows that 624 km^2 and 225.5 km^2 of agroforestry land changed into shrub/woodland and farmland, accounting for 35.7% and 12.9% of the total, respectively. We also con-

firmed during a focus group discussion that agroforestry LU practices are a tradition of the native peoples in the study area that needs to be enhanced.

The total area of settlement that increased by 66.9 km^2 mainly came from shrub/wood and farmland (Table 4), showing remarkable increases in new built-up land. This suggests the clearing of shrub land and vegetation over the period of the formation of new settlements. According to Dessalegn (2003), large-scale resettlement programs that were carried out during 1984/1985 in Ethiopia involved considerable LU changes by clearing large areas of vegetation to build homesteads, acquire farmland, and access roads. This kind of scenario is also likely the reason for the new demands for water, energy, and food (Biggs et al. 2015).

The LU change matrix also shows extensive LU cover changes that placed pressure on water, energy, and food production. This condition requires understanding the inter-linkages between the land and WEF nexus resources. The synergies between LU classes and WEF were analyzed using SNA (Fig. 7). Based on the changes detected over the entire period, the LU patterns helped to consolidate the bilateral impacts on WEF systems.

Impact of LULC Changes on Energy Sources

LULC changes have both direct and indirect impacts on the environment and associated services, particularly on services using hydropower as their major energy source. Considering the average percentage annual rates of change for different LULC types, forest, shrub land and farmland declined annually by − 4.7%, − 3.9%, and 1.6%, respectively, while agroforestry, settlement, and grassland increased annually by 18.2%, 2.4%, and 1.8%, respectively. This indicates that the widespread use of fuelwood and illegal logging resulted in sedimentation, siltation and destruction, and even the drying of power generating reservoirs. The use of wood as an energy source is also linked with LULC change.

The main use of the world's wood is not as building materials, paper, and other supportive products but as fuel (Parikka 2004). Wood provides many people, especially those in poor and rural households, with their primary source of energy (Sreevani 2018). Maes and Verbist (2012) estimated that 79% of the total traditional energy consumed in developing countries is fuelwood, and between 60

Table 4. LULC transition matrices (km^2) for the initial and final reference years (1986–2019)

LULC classes		2019								
		AF	BL	FL	F	S	GL	SWL	W	Total
1986	AF	**784.4**$^{95.4}$	0.00	10.9	16.1	1.3	8.4	1.3	0.02	822.4
	BL	0.3	**1.2**$^{25.9}$	0.7	0.02	1.3	0.8	0.22	0.0	4.5
	FL	225.5	0.5	**297.3**$^{42.6}$	43.8	80.8	28.6	20.9	0.02	697.5
	F	64.3	3.1	24.8	**78.5**$^{23.3}$	64.7	7.7	83.7	9.1	336.0
	S	48.3	17.6	44.1	4.1	**140**$^{41.1}$	19.7	65.7	1.1	340.6
	GL	1.6	0.0	0.0	0.0	0.0	**8.5**$^{84.4}$	0.0	0.0	10.1
	SWL	624.4	7.1	24.8	24.2	119.4	53.1	**221.7**$^{20.6}$	2.4	1076.8
	W	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.7**$^{93.1}$	0.7
	Total	1748.3	29.5	402.7	166.8	407.5	126.9	393.6	13.3	3288.6
	Gain	963.9	28.3	105.4	88.2	267.5	118.8	171.8	12.6	

The bold diagonal numbers indicate LC areas (km^2) that remained unchanged between 1986 and 2019, while the other statistics show the area of specific LULC that changed to another class

AF agroforestry, *FL* farmland, *BL* bare land, *F* forest, *S* settlement, *GL* grassland, *SWL* shrub and woodland, *W* water

and 69% of this amount is in Sub-Saharan Africa. This indicates a peculiar future for a country like Ethiopia, where more than 85% of rural people live without modern energy sources, making fuelwood the main energy sources. Presently, hundreds of millions of people completely rely upon wood for energy and cannot foresee a rapid transition to other energy sources due to the lack of access and affordability of both modern and alternative energy sources (e.g., solar and biogas).

Table 5 outlines how changes in agroforestry significantly reduce the annual sediment yield ($\beta = 0.856, p < 0.05$), which shows that such LU practices increase the potential for annual and perennial rivers to be used as water sources (Kanshie 2002). Today, soil loss by erosion is a global that adversely affects the reservoirs built for different purposes; this kind of environmental pressure requires the expansion of agroforestry LU practices. Similarly, Table 5 indicates that settlement significantly reduced energy supply ($\beta = -0.165$, $p < 0.05$) and energy use ($\beta = -0.122, p < 0.05$). This shows that expansion of settlement was related to population growth and increase in energy demands, leading to land degradation through fuelwood scarcity. It was determined from the key informants and focus group discussions that the local community potentially depends on traditional energy sources, which is the primary cause of the decline in forest, shrub, and woodland in the study area.

The correlation between LU classes and energy sources in the study area (Fig. 4) indicates that modern energy sources have a significant positive correlation ($r \geq 0.85$) with agroforestry. This shows that agroforestry LU practices reduced soil erosion and sedimentation, which affects the water source potential of different reservoirs. A significant negative correlation ($r > -2.8$) was also found between forest and modern, alternative, and collected fuelwood energy sources (Fig. 4). These observations indicate that forest loss affected both traditional and modern energy sources.

Changes in shrub and woodland significantly affected the energy supply ($\beta = 0.019$, $p < 0.05$), which is strongly linked to the local community using firewood and charcoal (Table 5). This result indicates that the magnitude and relevance of the land degradation process is likely to increase unless important shifts are made in an energy consumption patterns.

To understand the land-energy nexus resource inter-linkages through SNA, we used nexus attribute variables[1] collected from the local community. The

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[1] (L1 = land security, L2 = land size, L3 = land degradations, L4 = agricultural expansions, L5 = soil erosion, L6 = biodiversity loss, L7 = land uses, L8 = land tenure, L9 = land transfer, L10 = land marketing, L11 = land grabbing, L12 = land improvement, L13 = land features, L14 = soil and water conservations, E1 = traditional energy, E2 = energy demand, E3 = rural electrification, E4 = alternative energy, E5 = modern energy, E6 = energy security, [1]E7 = energy supply, E8 = energy sources, E9 = energy efficiency, E10 = energy consumptions, water security (W1), hydrological variability (W2), droughts and floods (W3), water supply (W4), improved Water (W5), small reservoirs (W6), irrigation (W7), water demand (W8), water sources (W9), water management (W10), water use (W11), water infrastructure (W12), sedimentation (W13), crop production (F1), annual Yield (F2), food processing (F3), fertilizer use (F4), mechanization (F5), food demand (F6), food supply (F7), crop biomass (F8), food assistance (F9), food availability (F10), food prices (F11), income (F12), livestock and fish (F13), food security (F14).

Table 5. Coefficients of WEF resources for each LU types using general linear model

Dependent variables (WEF nexus variables)	Independent variables (LULC types)									
	AF		FL		F		S		SWL	
	β	SD	β	SD	β	SD	β	SD	β	SD
Water										
Annual precipitation (mm)	0.087	0.014	0.045*	0.01	− 0.0264**	0.001	0.840*	0.016	0.0251	0.012
Sediment yield (tons)	− 0.32	0.207	0.0368	0.02	0.1562*	0.011	0.183	0.019	0.057*	0.006
Annual sediment load (tons)	− 0.69**	0.187	0.0482*	0.004	0.0856*	0.002	0.258*	0.049	0.03*	0.005
Constant	9.18	0.021	68.43	0.059	25.53	0.065	16.5	0.049	39.2	0.0058
R^2	0.898		0.983		0.943		0.838		0.832	
Energy										
Annual precipitations (mm)	0.972	0.052	− 0.0382**	0.002	0.2183*	0.011	0.171	0.046	0.117	0.015
Sediment yield (ton)	− 0.856*	0.014	0.019**	0.001	0.029*	0.003	0.022	0.005	0.162	0.016
Energy supply (%)	− 0.48	0.034	0.118	0.01	− 0.516**	0.01	− 0.165*	0.014	0.019*	0.014
Energy use (%)	0.14	0.007	0.053	0.01	0.0233	0.011	− 0.122*	0.025	0.056	0.013
Constant	15.7	0.071	22.12	0.066	27.81*	0.026	18.9*	0.038	11.8	0.025
R^2	0.998		0.942		0.898		0.992		0.899	
Food										
Food availability (%)	0.09	0.032	0.026*	0.001	− 0.007**	0.002	− 0.458**	0.042	0.023**	0.01
Food accessibility (%)	1.23**	0.046	0.046	0.012	0.044	0.01	− 0.488	0.012	0.021	0.005
Food stability (kg/ha)	0.197	0.982	0.086	0.013	-0.221**	0.181	0.034	0.01	0.161	0.012
Constant	26.16*		37.8		14.86		24.62*		12.59	
R^2	0.998		0.992		0.962		0.983		0.898	

*, **Statistical significance at $p < 0.05$ and $p < 0.001$

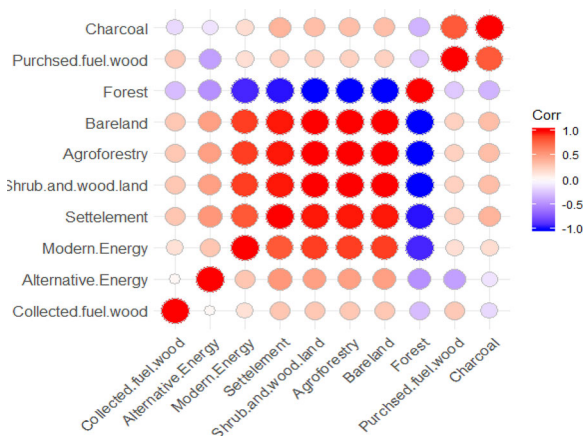*AF* agroforestry, *FL* farmland, *F* forest, *S* settlement, *SWL* shrub and woodland

Figure 4. Association between LULC classes and energy-related variables.

results of the SNA indicate that the network density between land and energy was 24.6%, which represented sparse density as rated by Prell et al. (2009). This sparse density reveals that the growing pressure on LU change was overlooked, and the extent of its adverse effects on energy sources has received lim-

ited attention. The maximum *Degree* centrality ($K = 8$) was recorded for soil erosion (L5) and biodiversity loss (L6), which are important players for mobilizing the network and bringing others nexus resources together.

Betweenness Centrality indicates the shortest path between land and energy nexus attributes, which are the most informative values available to determine the importance of a nexus attribute with respect to its neighbors. The linkages between LU and energy attributes showed that biodiversity loss (L6) has high *Betweenness Centrality* ($bv = 43.57$) and thus acted as an element of the network carrying disconnected segments together to maintain the nexus trade-off. According to Bodin and Crona (2009), natural resources holding high *Betweenness Centrality* are important for long-term resource management planning and presenting new and divers ideas to the network. Therefore, to maintain the synergy between LULC change and energy, nexus-based approach will be needed to meet the combined demands of energy for the population and economic growth.

Impact of LULC Change on Water Resources

The result of LULC change analysis showed that water bodies increased from 1.09 in 1986 to 11.93 km^2 in 2019. This could be attributed to the overflow of Abaya Lake, into which the Gidabo and Bilate Rivers flow. However, the responses of the key informants and focus group discussions indicate that small water bodies, such as local rivers, springs, streams, and ponds, decreased, even showing some drying due to land degradation in the last three decades.

Table 5 shows that agroforestry LU significantly reduced the annual sediment load ($\beta = -0.69$, $p < 0.001$). However, changes in forest significantly increased sediment yield ($\beta = 0.1562$, $p < 0.05$) and annual sediment load ($\beta = 0.0856$, $p < 0.05$). This indicates that LU change affected the hydrological variability.

According to Negewo (2018), the total observed and simulated sediment yield (load) between 1990 and 2010 was 3,442,064 and 3,446,300 tons, due to LULC changes in the study area. Similarly, studies on the Gilgel Gibe III hydroelectric dam in Ethiopia, into which the Gidabo River flows, indicated a high rate of sedimentation due to LC dynamics (Hathaway 2008). Thus, due to sedimentation, water for hydropower reservoirs was highly interrupted, and the country's electricity supply was irregular.

LULC changes and water resources have strong linkages. The SNA result between land and water, with node ($V = 28$) and edges ($E = 76$), indicates high *Closeness* centrality and *Betweenness* centrality values (≥ 0.5) for land and water attributes. These results reveal that the quick connection with the wider network and bridges between networks defined the *Closeness* and *Betweenness,* respectively. Therefore, managing the land and water nexus attributes showing maximum *Closeness* centrality and *Betweenness* centrality values will keep the synergy between land and water.

Figure 5 depicts the predicted probabilities of the network measures for the three centrality measures in the land–water nexus. These measures are affected by their direct or indirect linkages. The slope of direct links starts at a very high degree baseline probability, and it is only marginally positive, demonstrating that direct links do not offer a significant advantage in predicting mediation between nexus resources. In the nexus resource management, this result indicates that indirect impact of nexus attributes needs more attention, as the direct network shows only a unidirectional impact on the other network.

In general, the findings show that the bilateral inter-connections between land–energy nexus resources in the study area have not been given much attention. This will lead to degradation of nexus resources. Therefore, to improve the inter-linkage between LULC change and water, nexus resource users should invest in building a network between
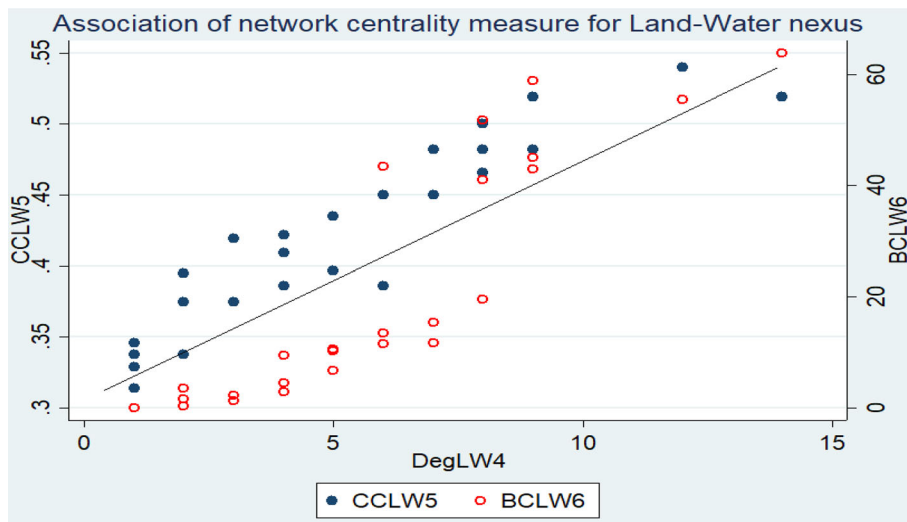

Figure 5. Relationship between *Betweenness* centrality, *Closeness* centrality, and the *Degree* for land–energy nexus. (LW = Land–water, CCLW5 = *Closeness* centrality, BCLW5 = *Betweenness* centrality, DegLW4 = *Degree*).

land and energy nexus resources to develop effective conservation strategies.

Impact of LUCC Change on Food Security

Future agricultural and food systems are closely related to future LULC, a key factor in the food–environment nexus (Stein et al. 2014). The results of the LULC revealed a decline in forest land, shrub land, and farmland. This kind of conversion has occurred at the expense of agroforestry and grassland in the upper and lower parts of watershed as sources of food security. Table 5 shows that food security is significantly influenced by agroforestry ($\beta = 1.23$, $p < 0.001$) and forest ($\beta = -0.22$, $p < 0.001$) LU changes. Increases in agroforestry LU classes increased food accessibility by producing integrated food and related agroforestry ecosystem services, while unit changes in forest land reduced the temporal dimensions of food (food stability).

Figure 6 illustrates how different LUs act as sources of food for the local community. Farmers in the lower part of the watershed noted that grassland covers 66.2% of their food sources. However, over the last 3 decades, due to induced LU changes, this area has been exposed to agro-ecological changes, which also affected food sources, such as crops, honey production, and medicinal plants.

The climatic condition of the area over the last three decades revealed high rainfall variability, frequent floods, and droughts, which constrained the ability of the study area to produce reliable food supplies. LULC changes linked with climatic vari-

ability, which represent the nucleus of agriculture and livestock in rural areas. Consequently, improper LU changes and lack of conservation have been identified as possible causes of LULC changes that affect food security. Therefore, a holistic approach that integrates LU change reclamation and allows evaluation of the various implications of current decisions on the projected pathways is needed.

Impact of LULC on the WEF Nexus

The increasing population, urbanization and unlimited human demands place increasing stress on key natural resources, which require a nexus approach (Terrapon-Pfaff et al. 2018). In our current study, we extended nexus resources to include land as a component of the WEF nexus, considering land as a central point, with all potential connections mapped out. The results of the analysis of LULC changes from a WEF nexus resource perspectives are outlined in the nexus matrix (Table 6). The summary of the nexus matrix table indicates that 12 nexus inter-linkages exist among these nexus resources when considering all LU classes as land: these are *Land–Water, Land–Energy, Land–Food, Water–Energy, Water–Food, Energy–Food, Food–Energy, Food–Water, Food–Land, Energy–Water, Energy–Land and Water–Land.* These are in agreement with the findings of Laspidou et al. (2019), who noted 24 unique sequences among the water–climate–land–food–energy nexus in total.

The dynamic LU changes in the study period occurred due to rapidly increasing demands for
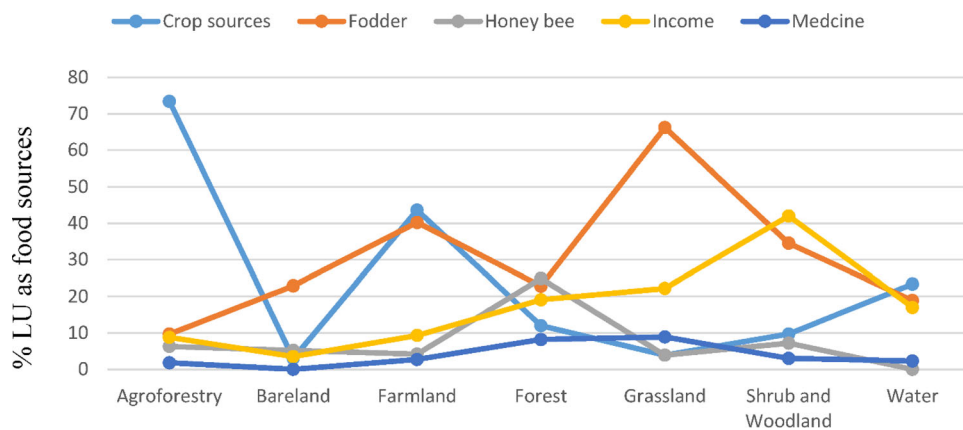

Figure 6. Land use as a source of food in the study area.

Table 6. Nexus matrix table showing the relationship between LU and WEF system

LULC types	Water	Energy	Food
AF	Retain water for crops	Woody biomass	Sources for trees and crops
	Maintain water quality	Protect sedimentation	Ecosystem services,
	Protect the watershed	Biofuel plants	Local economic capital
BL	Water conservation	Alternative energy	Food stress
	Water loss	Grid infrastructure	Drought and shock
	Evapotranspiration		
FL	Water demand	Biofuel production	Food production
	Irrigation water	Pumping,	
	Freshwater withdrawal	Mechanization	
F	Regulate water flow,	Fuel wood,	Forest food
	Regulate climate and maintain ground water recharge	Carbon regulation, Sedimentation control	Roots and tubers
GL and SWL	Regulate small water body	Biogas	Pastures,
	provide freshwater	Local energy sources	Forage for ruminants
S	Water demand and supply	Domestic energy consumption	Food demand and supply
	Waste water production		
	Flooding	Industrial energy consumptions	
W		Hydropower	Irrigation water, livestock water use, fisheries
		Water pumping and distributions	

AF agroforestry, *BL* bare land, *FL* farmland, *F* forest, *GL* grass land, *SWL* shrub and wood land, *S* settlement, *W* = water body

water, energy, and food. Forest decline in the study area coincided with changes in demographics and the socio-economic situation in Ethiopia (Melese 2016). Thus, the demands for construction material and fuelwood are depleting existing LUs at an alarming rate.

LULC changes have direct impacts on hydrologic systems within the watershed, resulting in soil erosion, sedimentation, and flooding, which seriously affect the water sources, energy production and food production. The study area features a large dam as a source of irrigation water supply. Unless conservation practices are undertaken in the upper watershed, this dam may face risk of surface runoff and stream flows.

The considerable increases in the area's settlement by 121.28 km^2 during 1986–2019 (Table 3) have had profound impacts on various environmental components, which disturbed the ecosystem providing water, energy, and food. A study by Patra et al. (2018) showed that urbanization has important impacts on changes in demographic characteristics and the transformation of the physical landscape. To improve synergetic management, building linkages among nexus resources is vital. Such linkages are often created to support and maintain combined networks. In this study, we used SNA model to examine how land, water, energy, and food link with

one another directly and indirectly via bridging management across each other (Fig. 7).

Based on the nexus attributes identified, the network diagram featuring 52 nodes ($V = 52$) and 471 edges ($E = 471$) was computed. The result shows a low level of connectivity for land tenure (L8) and land transfer (L9), while maximum connectivity was recorded for food demand (F6), food assistance (F9), and food availability (F10) from the four nexus resource attributes (Fig. 7). This indicates that the direct inter-connections of nexus attributes were centered on food, rather than land, water, and energy.

The direct links in the SNA diagram (Fig. 7) indicate mutual interest, shared preferences, and decreased uncertainty between nexus resources. However, a food centered approach will result in the unsustainability of other nexus resources, and the link from land to water indicates the potential management of land directly affects water sources, without considering complementary impacts.

Based on land-WEF nexus linkages, the maximum *Degree* centrality was computed for hydrological variability (W2, $K = 23$) and crop production (F1, $K = 22$). This indicates that nexus resources with a high *Degree* centrality are more likely to be considered as determinant resources because maximum inter-linkages mean greater opportunities for
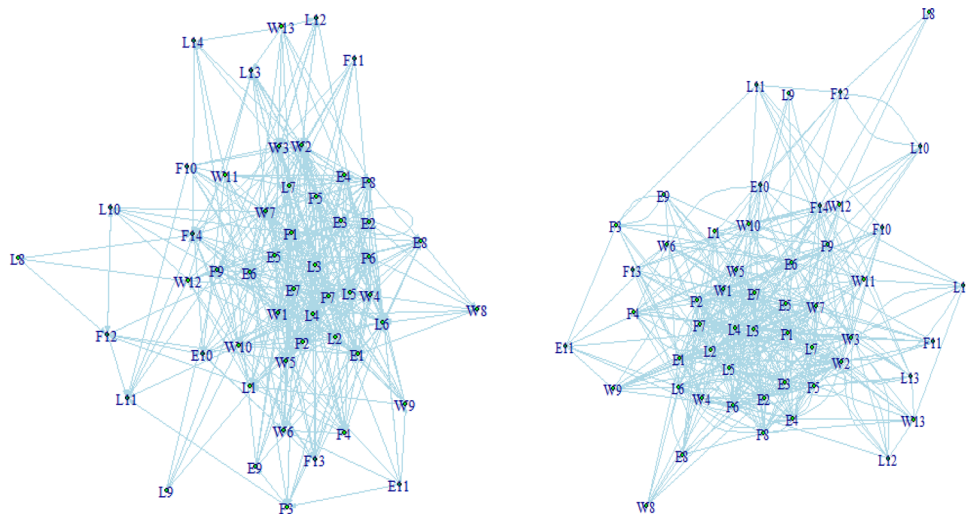
Figure 7. Direct (left) and indirect (right) networks among water, energy, food, and land.

environmental livelihood security (Biggs et al. 2015). Similarly, the maximum *Betweenness* centrality was acquired for hydrological variability (W2, bv = 145) and energy security (E6, bv = 178), which indicates that these nexus resources are more likely to serve as a bridge in the network. This means that the concern in managing energy and water should serve as the basis for overall LWEF nexus resources. Understanding the complementary of water and energy on nexus resource networking is important to consider agricultural land expansion for food production.

Understanding LULC changes and the WEF nexus from a microscale enables a joint assessment of nexus resources with the environment. The SNA that we built to link the four nexus resources was found to be a useful tool to show the synergies and trade-offs among nexus resources. In general, we found that understanding the complex inter-linkages of nexus resources using simplified tools and approaches helped to determine the current strengths and opportunities to identify the nexus resources importance for planning and policy making hot for planning and policy making at the grass-roots levels.

NEXUS RESOURCES CONCERNS AND POLICY IMPLICATION FOR THE FUTURE

It is increasingly clear that effective and sustainable solutions for water, energy, and food will require a greater understanding and consideration of the role of LULC changes and the close linkages between these resources. In the last century, the business-as-usual approach failed because it is too linear for today's natural resource management, which instead requires complex and interdependent resources through a common framework. New circumstances will require new designs and ways of thinking to produce flexible forms of governance. In response, the World Economic Forum (Leck et al. 2015) developed the idea of a nexus to achieve sustainable development goals and proposed an integrated approach for sustainable resource management (Biggs et al. 2015). This has yielded promising results and facilitated understanding between the scientific community and decision-makers.

Even though the focus of scholars on WEF nexus has recently increased (Terrapon-Pfaff et al. 2018), so far, the focus of discussion and applications of the nexus was on production by maintaining the balance between water and energy with limited attention on land, particularly in Sub-Saharan Africa. This underscores the fact that major nexus challenges are faced on a local scale and exert pressure on LU management. In the context of Ethiopia, the frequent policy changes and its blurred policy implementation indicates a lack of sufficient concern for nexus resource management. As a result, the country faces frequent food insecurity even though it has an ample amount of land, water, and energy sources. Therefore, we suggest that understanding the impact of LULC changes on nexus resources will provide the means to achieve the mutual responsibility needed to collaborate and disrupt the

business-as-usual approach in nexus resource management. This process will require efforts of scholars to frame locally applicable and functional nexus framework.

Determining other ways to organize and develop the area toward sustainable nexus resource management entails a moral obligation to act on this knowledge. We may, however, need new institutional arrangements and administrative reforms to advance nexus implementation. Therefore, future research concerns should consider designing friendly nexus framing from a local to global level to improve the conceptualizations and communication of nexus issues. Finally, to maintain the balance between land, water, energy, and food and reclaim past LC loss, the current Ethiopian green legacy, which involves planting more than five billion tree seedlings per year, should be adopted and spread globally to safeguard the current and future demands for water, energy, and food by the year 2050.

CONCLUSIONS

It is important to understand how LULC changes affect the WEF nexus resources. This will inform the formulation of polices to minimize the adverse effects of future LULC changes. Some of the LULC changes noted in this study are increasing hydrological variability, energy supply, and food availability. Clearly, the demand of water, energy, and food resources under alarming population growth in the study area exerting pressure following rapid LULC.

This study shows that the major LULC changes in the watershed are agroforestry, shrub/woodland, forest and settlement. These changes have direct effects on water and energy sources, as well as food production. The results also indicate that more LULC changes are likely to take place as more LU is converted over time, thereby threatening the sources of water and energy, and likely affecting food sources in the future. Our results suggest the following. (a) Current independent land, water, energy, and food nexus resource/sector management will create trade-offs and result in nexus resources insecurity. (b) The enhanced application of policies integrating land, water, energy, and food nexus resources is vitally important. (c) Understanding LULC changes and estimating its impacts on WEF nexus resources, will ultimately improve the inter-linkages that require land as basic nexus component

that determines the production potential of the WEF nexus.

ACKNOWLEDGMENTS

REFERENCES

Abebe, T., Wiersum, K., Bongers, F., & Sterck, F. (2006). Diversity and dynamics in homegardens of southern Ethiopia. In: *Tropical homegardens* (pp. 123–142). Springer, Berlin.

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M., Horsley, J., Pauli, N., et al. (2015). Sustainable development and the water–energy–food nexus: A perspective on livelihoods. *Environmental Science and Policy, 54,* 389–397.

Bodin, Ö., & Crona, B. I. (2009). The role of social networks in natural resource governance: What relational patterns make a difference? *Global Environmental Change, 19,* 366–374.

Butts, C. T. (2008). Social network analysis with SNA. *Journal of Statistical Software, 24,* 1–51.

Chartres, C. J., & Noble, A. (2015). Sustainable intensification: Overcoming land and water constraints on food production. *Food Security, 7,* 235–245.

Chen, B., Han, M., Peng, K., Zhou, S., Shao, L., Wu, X., et al. (2018). Global land–water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. *Science of the Total Environment, 613,* 931–943.

Desta, S., & Coppock, D. L. (2002). Cattle population dynamics in the southern Ethiopian rangelands, 198097. *Rangeland Ecology and Management/Journal of Range Management Archives, 55,* 439–451.

Elias, E., Seifu, W., Tesfaye, B., & Girmay, W. (2019). Impact of land use/cover changes on lake ecosystem of Ethiopia central rift valley. *Cogent Food and Agriculture, 5,* 1595876.

Genet, M. (2017). Groundwater flow direction, recharge and discharge zones identification in lower Gidabo Catchment, Rift Valley Basin, Ethiopia. *Journal of Environment and Earth Science, 7,* 32–39.

Gessese, B. H. (2018). Impact of land use/land cover change on rural communities' livelihood of Ethiopia. *Journal of Ecological Environment Science, 6,* 1.

Grove, A. (1986). Geomorphology of the African Rift system. *Geological Society, London, Special Publications, 25,* 9–16.

Gulati, M., Jacobs, I., Jooste, A., Naidoo, D., & Fakir, S. (2013). The water–energy–food security nexus: Challenges and opportunities for food security in South Africa. *Aquatic Procedia, 1,* 150–164.

Hathaway, T. (2008). What cost Ethiopia's dam boom. A look inside the Expansion of Ethiopia's Energy Sector: International Rivers, people water, life.

Hoff, H. (2011a). Understanding the nexus: Background paper for the Bonn2011 Conference.

Hoff, H. (2011b). Understanding the nexus: Background paper for the Bonn2011 Nexus Conference. SEI.

Hurni, H., Abate, S., Bantider, A., Debele, B., Ludi, E., Portner, B., & Yitaferu, B., & Zeleke, G. (2010). Land degradation and sustainable land management in the highlands of Ethiopia.

Kanshie, T. K. (2002). Five thousand years of sustainability?: A case study on Gedeo land use (Southern Ethiopia).

Karlberg, L., Hoff, H., Amsalu, T., Andersson, K., Binnington, T., Flores-López, F., de Bruin, A., Gebrehiwot, S.G., Gedif, B., & Johnson, O. (2015). Tackling complexity: understanding the food–energy–environment nexus in Ethiopia's Lake Tana sub-basin. *Water Alternatives, 8.*

Ketema, H., Wei, W., Legesse, A., Wolde, Z., Temesgen, H., Yimer, F., & Mamo, A. (2020). Quantifying smallholder farmers' managed land use/land cover dynamics and its drivers in contrasting agro-ecological zones of the East African Rift. *Global Ecology and Conservation, 21,* e00898.

Krasuska, E., Cadórniga, C., Tenorio, J. L., Testa, G., & Scordia, D. (2010). Potential land availability for energy crops production in Europe. *Biofuels, Bioproducts and Biorefining, 4,* 658–673.

Kurian, M. (2017). The water–energy–food nexus: Trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environmental Science and Policy, 68,* 97–106.

Laspidou, C. S., Mellios, N., & Kofinas, D. (2019). Towards ranking the water–energy–food–land use-climate nexus interlinkages for building a nexus conceptual model with a heuristic algorithm. *Water, 11,* 306.

Leck, H., Conway, D., Bradshaw, M., & Rees, J. (2015). Tracing the water–energy–food nexus: Description, theory and practice. *Geography Compass, 9,* 445–460.

Lee, S.-H., Taniguchi, M., Mohtar, R., Choi, J.-Y., & Yoo, S.-H. (2018). An analysis of the water–energy–food–land requirements and CO_2 emissions for food security of rice in Japan. *Sustainability, 10,* 3354.

Leese, M., & Meisch, S. (2015). Securitising sustainability? Questioning the 'water, energy and food–security nexus'. *Water Alternatives, 8.*

Maes, W. H., & Verbist, B. (2012). Increasing the sustainability of household cooking in developing countries: Policy implications. *Renewable and Sustainable Energy Reviews, 16,* 4204–4221.

Mehta, V. K., Haden, V. R., Joyce, B. A., Purkey, D. R., & Jackson, L. E. (2013). Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California. *Agricultural Water Management, 117,* 70–82.

Melese, S. M. (2016). Effect of land use land cover changes on the forest resources of Ethiopia. *International Journal of Natural Resource Ecology and Management, 1,* 51.

Meshesha, D. T., Tsunekawa, A., & Tsubo, M. (2012). Continuing land degradation: Cause–effect in Ethiopia's Central Rift Valley. *Land Degradation and Development, 23,* 130–143.

Mohtar, R. H., & Lawford, R. (2016). Present and future of the water–energy–food nexus and the role of the community of practice. *Journal of Environmental Studies and Sciences, 6,* 192–199.

Otte, E., & Rousseau, R. (2002). Social network analysis: A powerful strategy, also for the information sciences. *Journal of Information Science, 28,* 441–453.

Pahl-Wostl, C. (2017). Governance of the water–energy–food security nexus: A multi-level coordination challenge. *Environmental Science and Policy.*

Parikka, M. (2004). Global biomass fuel resources. *Biomass and Bioenergy, 27,* 613–620.

Patra, S., Sahoo, S., Mishra, P., & Mahapatra, S. C. (2018). Impacts of urbanization on land use/cover changes and its probable implications on local climate and groundwater level. *Journal of Urban Management, 7,* 70–84.

Pfister, S., Bayer, P., Koehler, A., & Hellweg, S. (2011). Environmental impacts of water use in global crop production: Hotspots and trade-offs with land use. *Environmental Science and Technology, 45,* 5761–5768.

Prell, C., Hubacek, K., & Reed, M. (2009). Stakeholder analysis and social network analysis in natural resource management. *Society and Natural Resources, 22,* 501–518.

Rasul, G. (2014). Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region☆. *Environmental Science and Policy, 39,* 35–48.

Ringler, C., Bhaduri, A., & Lawford, R. (2013). The nexus across water, energy, land and food (WELU): Potential for improved resource use efficiency? *Current Opinion in Environmental Sustainability, 5,* 617–624.

Searchinger, T., & Heimlich, R. (2015). Avoiding bioenergy competition for food crops and land. *Creating a Sustainable Food Future,* 1–44.

Seyoum, W. M., Milewski, A. M., & Durham, M. C. (2015). Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley lakes, East Africa. *Hydrological Processes, 29,* 4312–4324.

Spera, S. A., Galford, G. L., Coe, M. T., Macedo, M. N., & Mustard, J. F. (2016). Land-use change affects water recycling in Brazil's last agricultural frontier. *Global Change Biology, 22,* 3405–3413.

Sreevani, P. (2018). Wood as a renewable source of energy and future fuel. In: *AIP Conference Proceedings.* AIP Publishing LLC, p. 040007.

Stein, C., Barron, J., & Moss, T. (2014). Governance of the nexus: From buzz words to a strategic action perspective. *Nexus Network Think Piece Series, Paper, 3,* 1–23.

Sušnik, J., Chew, C., Domingo, X., Mereu, S., Trabucco, A., Evans, B., et al. (2018). Multi-stakeholder development of a serious game to explore the water–energy–food–land–climate nexus: The SIM4NEXUS approach. *Water, 10,* 139.

Temesgen, H., Wu, W., Legesse, A., Yirsaw, E., & Bekele, B. (2018). Landscape-based upstream–downstream prevalence of land-use/cover change drivers in southeastern rift escarpment of Ethiopia. *Environmental Monitoring and Assessment, 190,* 166.

Terrapon-Pfaff, J., Ortiz, W., Dienst, C., & Gröne, M.-C. (2018). Energising the WEF nexus to enhance sustainable development at local level. *Journal of Environmental Management, 223,* 409–416.

Waughray, D. (2011). Water security the water–food–energy–climate nexus: The World Economic Forum water initiative.

Weitz, N., Nilsson, M., & Davis, M. (2014). A nexus approach to the post-2015 agenda: Formulating integrated water, energy, and food SDGs. *SAIS Review of International Affairs, 34,* 37–50.

WoldeYohannes, A., Cotter, M., Kelboro, G., & Dessalegn, W. (2018). Land use and land cover changes and their effects on the landscape of Abaya-Chamo Basin, Southern Ethiopia. *Land, 7,* 2.

Yared, B. (2019). *Estimation of catchment sediment yield using SWAT Model (Case Study Gidabo Dam, Rift Valley Basin, Ethiopia).* Addis Ababa University.