Spatial Heterogeneity and Fragmentation Trends of Ecosystem Services: The Case of Highland Watershed

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Abstract

Landscape fragmentation and heterogeneity are poorly understood and acknowledged in the Ethiopian highlands. Land fragmentation has both direct and indirect relationship with productivity, water resource, sediment load and enviorment. This study aims to spatially characterize the state of heterogeneity and fragmentation of ecosystem services (ES) since 1957. The data were obtained from the aerial photograph and field data. Indices were used to analyse fragmentation and heterogeneity. A total of 1869 parcels were mapped using GPS. Average crop landholding size and number of parcels per household was 0.18 ha and 4.5, respectively. The density of cropland was 150 parcels/100 ha and of shrubland was one parcel/100ha. The highest number, density, dominance and smallest size were revealed for food providing land parcels. However, cultural service providing parcels are larger in size. The increase of demand and the different use rights for ESs caused to increase the heterogeneity of the land cover types. The analyses indicated that there has been an increasing trend of land fragmentation. Such condition deteriorates productivity of the resource base and diminishes benefits from the ESs. The study recommends research and policy tools (such as clustering similar land units) to limit further fragmentation and calls for more work on how fragmentation affects productivity, water, environment and land management decisions.
Keywords: Cultural services, Density, dominance, Landscape metrics, Parcel

1. Introduction

Land fragmentation changes the way the landscape functions, and that directly links to the environment, water resources, and wetlands. The pattern, composition and characteristics of the landscape are affected by the level of subdivision (Donnelly & Evans, 2008). Parcelization of land is the result of landscape management and socio-economic changes (Demetriou, 2014). These situations have a direct influence on economic development and sustainability (Malinowska & Szumacher, 2013). In the Ethiopian highlands, population growth has proportionally increased demand for agricultural products and is substantially linked to landscape transformations (Wondie et al., 2016). When holdings are subdivided into many small parcels, land use becomes more intensified and less coordinated across the watershed. This weakens environmental quality by accelerating soil erosion, and lowering infiltration, so more rainfall becomes surface runoff. As a result, streamflow becomes quick rise and quick drop, groundwater recharge declines, and sediment delivery to rivers increases. These processes reduce overall water availability and reliability, and they also raise the risk of downstream flooding and siltation of water bodies, which damages aquatic habitats and reduce water quality.

Wetlands are especially sensitive to these fragmentation driven changes because they depend on stable catchment hydrology and clean water inputs. Increased runoff and sediment loads from fragmented, intensively cultivated parcels can bury wetland vegetation, reduce wetland depth, and alter wetland hydroperiod (the seasonal duration of flooding). Land fragmentation is not only a land tenure or farm management issue but also a watershed scale environmental driver that can undermine water resources and wetland health unless land management and planning tools prioritize coordinated catchment and buffer protection.

There are different metrics/indices to explore spatial heterogeneity and fragmentation that are often used as indicators in determining the structure, function and mosaics of landscape elements (Yiet al., 1996; Hong, 1999; Leitao & Ahern, 2002; McGarigal et al., 2002; Wu et al., 2002; Zha et al., 2008). The metrics/indices used are patches, patch density, patch diversity, richness, evenness, variation, contagion and fractal dimension. These indices provide information on the state of the mosaicked physical features (including LCUTs and ESs) and landscape changes (Leitao & Ahern, 2002; Junhonget al., 2008; Malinowska &Szumacher, 2013) and help to deal with the relationship between landscape pattern and ecological processes (Cardille et al., 2005).

Understanding the status of land fragmentation and heterogeneity in the Ethiopian highlands is important to deliver decision support tools for policy makers. Such decision tools will enable relevant authorities to make appropriate interventions for reducing the pitfalls of fragmentation (Tan et al., 2006) and implement proper land management practices to enhance production in small landholding farmers. Therefore, the objective of this study was to spatially describe and identify the state of heterogeneity and fragmentation of ESs at a fine scale.

2. 2. Materials and Methods

2.1. Study area

The Tara Gedam watershed is located approximately at 12° 8’ 30” - 12° 10’ 30” N and 37° 43’ 35” - 37°46’ 05” E in the Amhara National Regional State (ANRS), northwestern Ethiopia (Fig. 1). The watershed is characterised by a rugged topography with an altitudinal range of 2000 - 2600 m. The watershed covered an area of 900 ha.

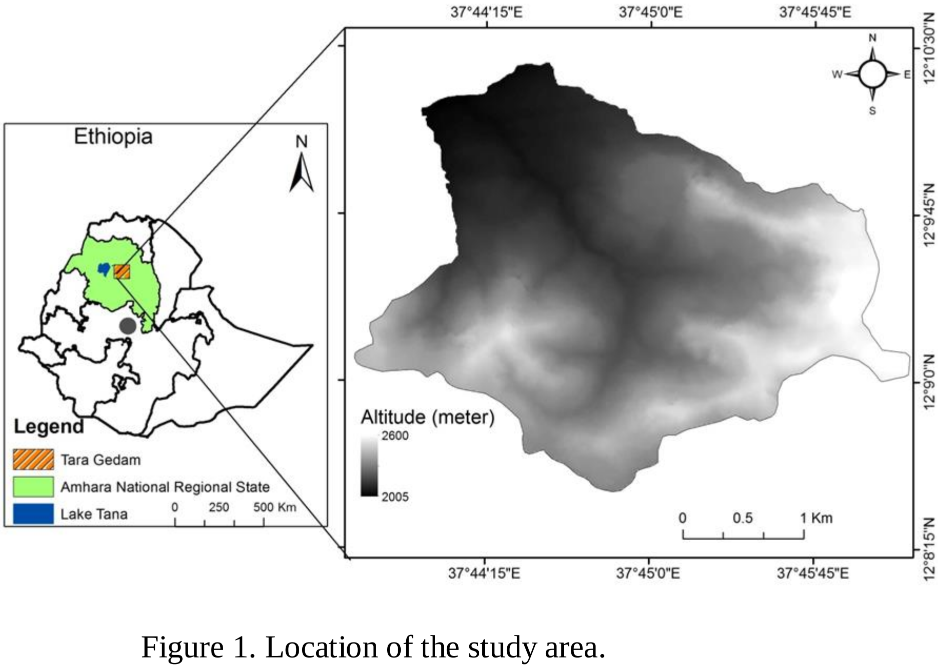

Figure 1. Location of the study area.

The average annual rainfall is 1175 mm, with the peak rainfall season between June and August and the dry season between December and April. The monthly mean temperature ranges from 18 to 34 °C.

2.2. Methods

2.2.1. Data preparation

The 1957, 1980 and 2013 datasets were used to synthesize the land cover/use types. The land cover of 1957 and 1980 was acquired from the interpretation of the aerial photograph using photogrammetric procedures. The land cover of 2013 was mapped using the data obtained from a field survey using GPS. The 2013 dataset was used to analyse the landscape (spatial) metrics both for LCUTs and for ESs. However, the 1957 and 1980 aerial photographs were used for LCUTs only. The field dataset of 2013 was used to generate fine scale and vector-based information; whereas aerial photographs were interpreted on the basis of polygons produced from the field data.

2.2.2. Field data collection

The field survey to collect point data using GPS was carried out between 2012 and 2013 (dry months). Point data for each parcel of the farm were collected as land mapping units (LMUs). The point data misplacement, deviation and errors were corrected by re-measurement and by the support of Google Earth. These point data were area-referenced (converting point into polygon feature data) to calculate area and perimeter of each parcel. Area and perimeter were described in hectare and meter, respectively. The GPS data were used to estimate the gaps and spaces of land that remained underutilised between neighbouring parcels. Spatial explicit representation of parcels in map forms was conducted prior to landscape metrics analyses. Field verifications were undertaken to check and readjust the corresponding land user. Individual farmers were met informally in their farmland to understand the benefits and demands of the local residents due to change of fragmentation.

Using GPS data, LCUTs were categorised into seven types namely: cropland (CR), fruit-based agroforestry (FAF), forestland (FO), grassland (GR), *Rhamnus*-based agroforestry (RAF), shrubland (SH) and tree-based agroforestry (TAF).

2.2.3. Classification of aerial photographs

Polygons derived from GPS data were the basis to classify the aerial photograph into different LCUTs. The polygons of each parcel of cropland, forestland, grassland and shrubland obtained using GPS were first mapped and prepared in vector format. The polygons in the vector (feature) format were superimposed on the stereo image. Assignment of the respective polygon to LCUTs of the 1957 and 1980 was conducted by marking manually (visual interpretation) using point feature. Point features were collected for the LCUTs, corresponding to the superimposed polygon data.

2.2.4. Classification scheme

The classification schemes, both for LCUTs and ESs, were defined and specified prior to analysis.

Table 1. Land cover classes and ecosystem services used in the classification scheme.

Land cover/use types (LCUTs)	**Characterization of features of the LCUTs**
Cropland (CR)	The land used for cultivation of annual crops such as cereals, pulses

Land cover/use types (LCUTs)	Characterization of features of the LCUTs
	and oil crops.
Forestland (FO)	Land covered with natural or plantation forest specifically used for fuelwood production, conservation and cultural values.
Grassland (GR)	Land under permanent pasture and grass used for cattle grazing or hay production.
Shrubland (SH)	Shrubs, bushes and young tree species managed for grazing, browsing and collecting wood for household use only.
Fruit-based agroforestry (FAF)	Land or a parcel used for annual crops integrated with fruit species (e.g. Maize [*Zea mays* L.] with *Carica papaya* L., *Psidium guajava* L., *Mangifera indica* L.).
Rhamnus-based agroforestry (RAF)	Land use integrating annual crops with *Rhamnus prinoides* L'Herit in space and time.
Tree-based agroforestry (TAF)	Land use integrating annual crops with trees in different spatial and temporal combinations.
Ecosystem services	**Characterization of features of the LCUTs**
Food	Products obtained from crops e.g. grains from maize, teff, sorghum and finger millet.
Flood protection and biodiversity conservation	Forest protected and used for environmental protection and conservation purposes.
Cultural/spiritual	Benefits obtained from the forests of churches or monasteries for spiritual/cultural services.
Feed	Products used by livestock, i.e. grasses or shrubs.
Wood-food- fruit	Products obtained from agroforestry practices, specifically from FAF, RAF and TAF in combination.

2.2.5. Landscape metrics

This study emphasises on spatial heterogeneity and fragmentation of the 2013 data for LCUTs and ESs using landscape metrics. The 1957 and 1980 data were used to analyse trend of heterogeneity. The analyses were focused on structural metrics, i.e. based on the physical configuration of LCUTs and the ESs. Spatial and non-spatial (statistical) analyses were conducted using the respective method (formula). The spatial component includes the attribute of classes and measurements, such as area (ha), perimeter, patch density, fractal dimension and effective mesh size(Rutledge, 2003). The non-spatial (statistics) describes the type and number of classes of LCUTs and ESs, proportions, coefficient of variation, human disturbances and diversity (McGarigal & Marks, 1994; Gustafson, 1998;Rutledge, 2003).

2.2.6. Heterogeneity

Heterogeneity gives emphasis on ecological structure represented by the mosaics of LCUTs and ESs. It was assessed by using patch mean, standard deviation, the coefficient of variation, class density, diversity and dominance (McGarigal& Marks, 1994; Malinowska & Szumacher, 2013). The homogeneity index (HI) was included to understand variations within and between classes. Standard deviation (SD) was used as a measure of absolute variation of the size of each parcel, but the coefficient of variation (CV) was used to measure relative variability (%) about the mean. The Shannon-Weiner index was chosen to calculate the diversity as an indicator of heterogeneity and complexity of LCUTs and ESs (Morelli et al., 2013).

2.2.7. Data analyses

*2.2.7.1. **Fragmentation analyses***

Fragmentation is often analyzed using indices (Hung et al., 2007). The attributes used to describe fragmentation were composition, configuration, shape and size (area) of each class. The quantitative characteristics used to analyse fragmentation were the number, size (area), perimeter, parcellation, proportion, class (patch) density (CD), shape complexity, human disturbance, fractal dimension and dispersion/aggregation of parcels (McGarigal& Marks, 1994). Shape complexity of LCUTs and ESs was measured using perimeter-to-area ratio and fractal dimension (Herold et al., 2005). The proportion of each class was used to look into the trend of human population with the subdivision of farm parcels.

3. Results

3.1 Characteristics of farm households

The average family size in Tara Gedam is 4.8 per household. The density of the population is about 213 individuals km^{-2}, which is slightly higher than the regional and national averages. The illiterate made up 30% of the 392 households. The average size of crop landholding per individual household was about 0.18 ha with an average number of parcels (plots) of 4.5, scattered in the watershed. However, the study conducted in the the central highland of Tigray of northern Ethiopia showed that the average number of plots is three and the average land holding is 0.39 ha (Beyene et al., 2006). Irrigation accounted for less than 10% of the total cropland area.

3.2 Spatial distribution of land cover/use types

Current land cover of cropland (CR), forest (FR), fruit-based agroforestry (FAF), grassland (GL), Rhamnus-based agroforestry (RAF), shrubland (SH) and tree-based agroforestry (TAF) was estimated at 26.04, 24.89, 0.55, 20.83, 3.97, 4.8 and 5.6%, respectively. The land covered by cropland and agroforestry practices, in combination, increased by three-fold between 1957 and 2013 while the areas of shrubland, forestland and grassland declined by 30, 50 and 60%, respectively (Fig. 2). Agroforestry practices, i.e. FAF, RAF and TAF, evolved from the crop producing parcels due to the integration of annual crops (cereals, pulses and oil crops) with trees/shrubs including fruits. Here, the three agroforestry practices (FAF, RAF and TAF) were placed independently due to the variation of the components integrated. The net land gain of CR, FAF, RAF and TAF was from the conversion of forests, grassland and shrubland

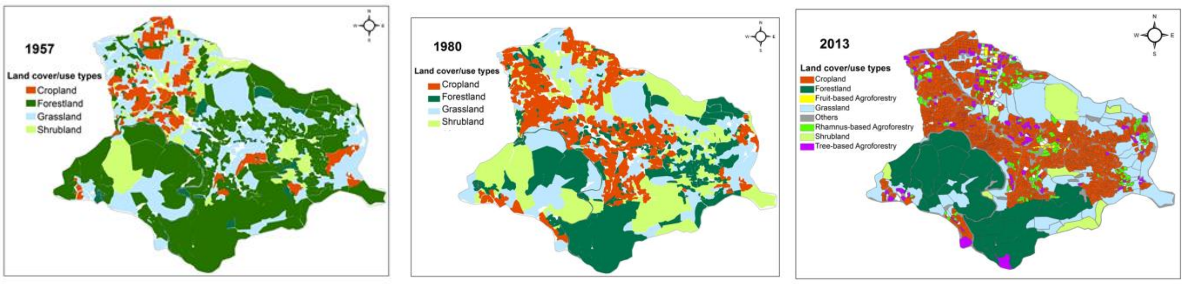

Figure 2. Spatial distribution of LCUTs in 1957, 1980 and 2013.

3.3 Spatial distribution of ecosystem services

The spatial distribution of the farm parcels providing various types of ESs in 2013 was dominated by food, feed, fruit and wood, whereas cultural/spiritual services accounted for the least coverage (Fig. 3). About 58% of the watershed area was covered by food, feed, fruit and wood (subsistence providing) producing parcels. Food producing parcels covered the largest (26%) and those providing cultural/spiritual services covered the least (8%). The flood protection and biodiversity conservation areas were estimated to cover about 22% of the parcels. The remaining land was covered by asphalt (road), paths, marginal/underutilised and rock.

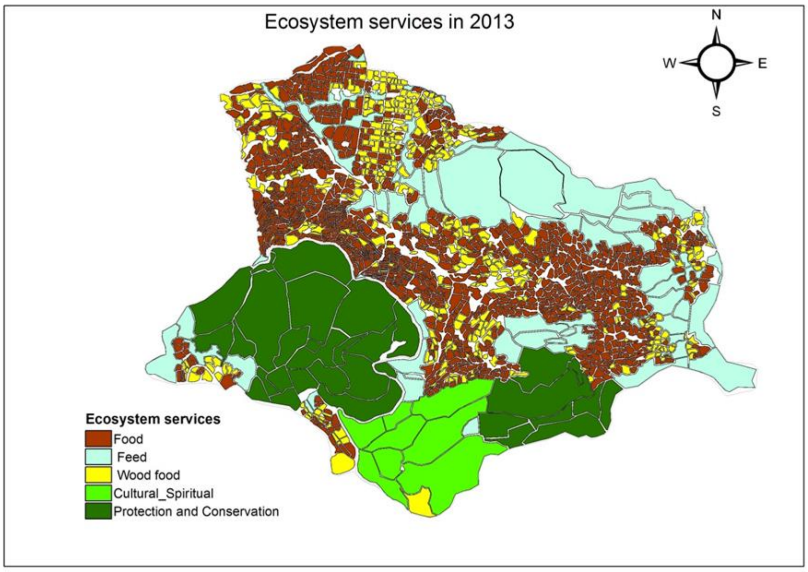

Figure 3. Spatial distribution of the various ecosystem services.

3.4 Description of ecosystem services

The mean area covered by parcels used for cultural/spiritual (CS) services was 8.5ha and was the highest. For parcels used for protection/biodiversity conservation (PC) and feed (FE), the mean areas were 5.9 and 3 ha, respectively. The SD also followed a similar trend. The parcels used to provide cultural/spiritual, protection/biodiversity conservation and feed services covered areas of 6.2, 5.2 and 4.1 ha, respectively (Table 3).

Table 2. Statistical description of the parcels is providing ESs.

Ecosystem services	Min (ha)	Max (ha)	Median (ha)	Mean (ha)	Sum (ha)	SD (ha)	CV (%)	Skewness (-)	N (-)
Cultural/Spiritual (CS)	2.50	21.38	8.45	5.8	67.6	6.22	458	1.49	8
Food (FO)	0.03	1.11	0.17	0.14	230.9	0.11	6	2.30	1333
Feed (FE)	0.18	23.73	2.96	1.93	189.7	4.09	565	3.63	64
Protection/Conservation(PC)	0.84	19.6	5.95	4.33	190.5	5.19	453	1.26	32
Wood-food-fruit (WF)	0.03	3.08	0.21	0.16	89.6	0.21	19	8.59	432

Min = Minimum, Max = Maximum, SD = Standard deviation, CV = Coefficient of variation and N = Number of parcels.

Parcel size variability was very high for fuelwood and energy (565%), cultural services (458%), and protection/conservation (452%), but very low for food providing parcels (6%). The low variability for food parcels reflects frequent ploughing, repeated modification, and ongoing subdivision to share land among extended families, which increases parcelization, fragmentation, and landscape heterogeneity. In contrast, church and state forest parcels that provide cultural and protection services are relatively stable, changing little because church forests are spiritually respected and state forests are protected by law.

3.5 Landscape metrics/indices for land cover/use types

The highest and lowest numbers of parcels were shown for CR (1333) and SH (9), respectively. Similarly, the highest and lowest densities were observed for CR (150/100ha) and SH (1/100ha), respectively. The calculated values of the metrics/indices were presented for the 2013 LCUTs (Table 3).

Table 3. Landscape metrics/indices of the LCUTs in 2013.

LCUT	Number of parcels	CD (N/100 ha)	SC (m/ha)	Mean (ha)	SD (ha)	CV (%)	HI (-)	DO (-)	PAR (%)	FD (-)
CR	1333	150	1034	0.14	0.11	65	1.0	2.97	71.19	1.69
FR	27	3	165	5.76	5.77	71	0.6	1.28	1.39	1.44
FAF	31	3	1091	0.13	0.07	44	1.0	1.48	1.60	1.59
GR	68	8	322	1.93	3.41	126	0.8	1.69	3.58	1.52
RAF	190	21	989	0.15	0.12	65	1.0	2.22	10.10	1.64
SH	9	1	199	2.48	5.88	124	0.6	0.89	0.43	1.40
TAF	211	24	858	0.18	0.27	115	1.0	2.25	11.22	1.63

CD = class density, SC = Shape complexity, SD = Standard deviation, CV = Coefficient variation, HI = homogeneity index, DO = Dominance, PAR = Parcellation and FD = Fractal dimension.

The study found that land cover/use types showed increasing parcel shape complexity, where more complex shapes indicate greater modification and fragmentation (Rutledge, 2003). Parcellation was highest in cropland (CR) and lowest in shrubland (SH), mainly driven by local land management, with soil erosion also breaking parcels into smaller pieces. Cropland became the dominant land use due to conversion from other types to meet rising food demand. Homogeneity indices near one for several land cover types suggest little size variation because of frequent subdivision, while shrubland and forest-related parcels showed greater size differences due to disturbance and ownership or use rights. Overall, the metrics over 56 years partially captured an increasing fragmentation trend (Table 4).

Table 4. Landscape metrics/indices for the LCUTs in 1957, 1980 and 2013.

Year	PR	EMS	DI	SC	HD	DO	FD
1957	4	294.00	0.48	548.74	0.09	2.77	1.63
1980	4	187.94	0.60	546.64	0.87	2.65	1.63
2013	7	159.71	0.65	554.22	2.48	2.63	1.64

PR = patch richness, EMS = Effective mesh size, DI = Diversity index, SC = Shape complexity, HD = Human disturbance, DO = Dominance and FD = Fractal dimension.

Cropland (CR) had the highest parcel number, class density, and dominance, while shrubland (SH) had the lowest. Fractal dimension values for CR and TAF were relatively high and changed very little from 1957 to 2013, showing that FD was not a useful indicator for tracking fragmentation trends over time. In contrast, landscape richness and diversity increased (patch richness from 4 to 7; diversity index from 0.48 to 0.65), alongside a strong rise in human disturbance (0.09 to 2.48). Diversity increased with human disturbance, suggesting growing demand for multiple ecosystem products led to more land modification, greater heterogeneity in land cover/use types, and a decline in natural and semi-natural areas, including shrinking church and community forests due to conversion to other land uses. Effective mesh size (EMS) dropped from 294 ha in 1957 to 159.7 ha in 2013, showing that landscape fragmentation intensified over time. Dominance (DO) also declined from 2.8 to 2.63, suggesting the landscape shifted from being dominated by fewer land cover/use types with lower human disturbance to a more mixed set of LCUTs, increasingly influenced by cropland (CR). This decline likely reflects conversion and replacement among LCUTs due to human intervention, consistent with Wondie et al. (2016), indicating a dynamic and continually changing landscape.

3.6 Metrics of ecosystem services

From the analyses of the 2013 data, the FO producing parcels showed the highest number of parcels (1333) and the lowest number of parcels was observed for CS. The FO and CS producing parcels showed a density of 150/100 and 1/100 ha, respectively. Due to the human disturbance, the mean and the SD values of the FO and WF producing parcels were the least compared with other ES providing parcels (Table 6). The human modification and change of parcels resulted in to have smaller farm parcel size. These ESs also showed the highest FD due to high fragmentation as a result of modification and frequent changes.
Table 2. The metrics of ecosystem services recorded in 2013.

Ecosystem services	Number (N)	CD (N/100 ha)	SC	Mean	SD	CV (%)	HI	DO	PAR (%)	FD
CS	8	1	166.4	8.4	6.2	73.6	0.5	0.8	0.4	1.4
FO	1333	150	1034.0	0.2	0.1	64.9	1.0	2.9	71.2	1.7
FE	64	7	301.1	3.0	4.1	138.1	0.8	1.7	3.4	1.5
PC	32	4	189.0	6.0	5.2	87.1	0.7	1.4	1.7	1.4
WF	432	49	922.8	0.2	0.2	100.5	1.0	2.5	23.0	1.6

CD = class density, SC = shape complexity, SD = Standard deviation, CV = Coefficient of variation, HI= Homogeneity index, DO = Dominance, PAR = Parcellation and FD = Fractal dimension.

The homogeneity index (HI) for FO and WF was closer to 1, whereas that of CS was the least (0.67). This showed the sizes (ha) of land parcels providing FO and WF had insignificant variation due to human modification and land use dynamics. However, CS and PC exhibited irregularities because of their semi-naturalness and less human intervention.

4. Discussion

4.1 The metrics of land cover/use types

Heterogeneity in the context of this study is the spatial variation, composition and size due to land management practices. The best explanatory index for heterogeneity is diversity (Wu et al., 2002; Song et al., 2008). The results showed an overall increase of diversity, i.e.from 0.48 in 1957 to 0.65 in 2013. This showed an extensive modifications of LCUTs were practiced since the 1950s. These dynamics of LCUTs increased due to the conversion of one LCUT to another to obtain the respective ES. For example, forestland was converted into cropland because of food demand by the increased population (Wondie et al., 2016). The detailed information obtained from 2013 data revealed the presence of different agroforestry practices due to the requirement for diverse ESs by the local people.

Changes in landscape diversity were mainly driven by whether agroforestry practices (FAF, RAF, and TAF) were present, since they increase the range of products available. Spatial heterogeneity in the watershed was linked to land subdivision, land redistribution policies, household factors, land quality, and environmental gradients. Forestland, shrubland, and grassland showed higher size variability (SD and CV), reflecting less human reshaping and differences in ownership (for example, small privately owned grassland parcels versus larger community grasslands). In contrast, cropland and some other land cover/use types had lower SD and CV, more uniform parcel sizes, sharp boundaries, and very high parcel densities (such as 150 parcels per 100 ha), indicating strong human modification and fragmentation. Overall, metrics like SD, CV, parcel density, skewn

Fragmentation of LCUTs was explained using number of parcels, SD, CV, FD and EMS. The higher number of parcels was revealed from CR, FAF, RAF and TAF. This attribute is because of conversion and subdivision of other land uses, e.g. forests and grasslands into these LCUTs. The number and density of croplands were the highest, which is an indication of higher fragmentation (subdivision) per unit area of croplands in Tara Gedam Watershed. The fragmentation status was also complemented by effective mesh size (EMS). The EMS showed a decreasing trend from 1957 to 2013.This implied that the watershed became more fragmented. The lower the effective mesh size, the more fragmented is the landscape, and the more disconnected the parcels are or vice versa (Jaeger, 2000; Baldi et al., 2006).

4.2 Status of ecosystem services

Class size of the LCUTs has the influence on the capacity of land to produce ESs to support the livlihoods of the local people. The smaller-sized parcels of cropland, fruit-based agroforestry, *Rhamnus*-based agroforestry and tree-based agroforestry practices provided food, feed, fruit, wood and related products. Smaller farm parcels produced insufficient products to support the household. This is because subdivision minimised effective production area (Donnelly & Evans, 2008). The presence of larger-sized plots, mainly, administered and managed by the Government and churches are allocated to forestland, which provides protection/conservation and cultural/spiritual services. For example, larger-sized patches of government-protected forest provide flood protection, headwater protection, microclimate improvement and biodiversity conservation. The concentrated patches of forest administered by the churches gave cultural, spiritual and religious services. The result showed that size determines the type of ESs obtained in the watershed. This, in turn, showed that parcel size has an effect on the type and amount of ESs produced.

Size also governs the diversification of products per unit area. The smaller the size of the parcels, the lesser is the possibility of product diversification. Most small farms are subjected to mono-cropping and are allocated to annual crops because of limitation of space. As a result, most of the farm plots (approximately 72%) have no timber or fruit trees and lesser activities of soil and water conservation structures. This is the outcome of land fragmentation that leads to low integration of farm practices for diversified products. Food producing parcels can be examples for this problem.

4.3 Heterogeneity of ecosystem services

Tara Gedam Watershed is endowed with a diverse mosaic of ESs due to the needs added by the farmers, community, Government and churches. Farmers focused on food, wood, feed and income generation. Community managed land parcels are mainly used for grazing and browsing. State protected forests, shrublands and grasslands are used for protection and conservation purposes, while the church-owned forests provide cultural and spiritual services. The trend in increased population has increased the land use intensification and diversification because of diversified demands. As a result, the diversity index (DI) for the mosaic of LCUTs increased from 1957 to 2013. The DI indicated the heterogeneity of LCUTs, which, in turn, indicated the increase in the demand of the people residing in the watershed. Since LCUTs are sources for ESs, the higher modification of LCUTs implicitly indicates human modification of the environment to obtain various types of ESs. This, in turn, contributed to the availability of diverse ESs.

Tara Gedam Watershed is endowed with diverse ESs compared with the nearby landscapes. The presence of protected forests for conservation and cultural/spiritual services indicated the diverse characteristics of ESs. This might be the consequence of various interested parties (farmers, communities, Government and churches). Due to its uniqueness and presence of heterogeneous ES, different ecological studies have been conductedin the Tara Gedam Watershed, such as floristic diversity (Zegeye et al., 2011), the pattern of forest seed dispersal (Abiyu, 2012) and soil variability (Workneh, 2008; Feyisa, 2012).

4.4 Fragmentation of ecosystem services

The average landholding size and number of plots in ANRS is less than one ha and 4.6, respectively (SANYU Consultants, 2009, unpublished). In the case of Ethiopia, the average number of plots is 2.3 per household (Gebreselassie, 2006). The average landholding size and number of plots in the central Tigray is 0.39 ha and 3, respectively (Beyene et al., 2006). However, in the case of Tara Gedam Watershed, the average size and number of plots providing different ESs were 0.78 ha and 4.5, respectively. A higher number of farm plots and smaller land size per household was documented. This is the outcome of fragmentation, which results in a negative impact on land productivity, agricultural technology use and sustainability. Sustainable provision of ESs from Tara Gedam watershed have been affected by the land is provided by parents for children as a capital to sustain their livelihoods in the form of inheritance or gift. Land redistribution also contribute fragmentation. Land degradation due to erosion and competition among different demands and land use types increased the conversion of one land use to another, e.g. conversion of forests to crop cultivation.

4.5 Consequences of fragmentation

The trend of land fragmentation has been worsening over time. This trend raises production costs, wastes time traveling between scattered plots, reduces effective land management and monitoring, and increases disputes between neighbors, including conflicts over runoff from upper fields. Fragmentation also discourages planting timber or fruit trees and worsens pressure on communal grazing areas, where small allocated parcels lead to overstocking. Overstocking causes soil compaction and accelerates erosion, degrading the environment and reducing land productivity, while sediment and nutrient runoff can further pollute water resources and increase siltation risks downstream, especially affecting wetlands that depend on clean inflows and stable catchment conditions. As these environmental impacts expand across the watershed, they can alter hydrological regulation, reduce water quality, and undermine wetland functions such as filtration, flood buffering, and dry season flow support.

5. Conclusion

Tara Gedam Watershed is more densely populated than many other Ethiopian highland areas, so it faces stronger land parcellation driven by inheritance or gifts, weak land management, and biophysical constraints. Similar evidence elsewhere shows that growing household size can increase plot numbers and reduce average plot size (Tan et al., 2006). In Tara Gedam, this fragmentation has reduced the efficiency of farming, raised labor and production costs, and contributed to declining productivity per unit area, which undermines food security and weakens ecosystem service (ES) provision. Beyond agriculture, fragmentation also harms the environment by encouraging intensive cultivation on small, scattered plots and limiting coordinated watershed management, which can increase soil erosion, sediment transport to streams, and degradation of water resources. As sediment loads rise, downstream wetlands become more vulnerable to siltation and reduced water quality, threatening wetland functions such as flood buffering, filtration, and dry-season water regulation. For this reason, the study emphasizes the need to understand land fragmentation and its implications for ESs within sustainable land management planning.

To respond, fragmentation assessment should not rely only on fractal dimension (FD), because it is not sufficient to capture long-term fragmentation trends on its own; it needs to be combined with other metrics. Practical solutions should focus on maximizing yield per unit area while also protecting water resources and wetlands by reducing erosion and sediment delivery through better land management and coordinated planning. Land consolidation, for example clustering adjacent farms, can support more efficient farming and make it easier to apply watershed-based soil and water conservation measures, but it requires political commitment and community consensus. In parallel, identifying minimum viable parcel sizes can help target suitable land management options, while off-farm livelihoods, family planning, and intensification can reduce pressure to subdivide land further. Further research should quantify economic losses and environmental impacts, including sedimentation risks to water resources and wetlands, across different agroecologies and social contexts

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