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The Implications of Plantation Forest-Driven Land Use/Land Cover Changes for Ecosystem Service Values in the Northwestern Highlands of Ethiopia

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Abstract: In the northwestern Highlands of Ethiopia, a region characterized by diverse ecosystems, significant land use and land cover (LULC) changes have occurred due to a combination of environmental fragility and human pressures. The implications of these changes for ecosystem service values remain underexplored. This study quantifies the impact of LULC changes, with an emphasis on the expansion of plantation forests, on ecosystem service values in monetary terms to promote sustainable land management practices. Using Landsat images and the Random Forest algorithm in R, LULC patterns from 1985 to 2020 were analyzed, with the ecosystem service values estimated using locally adapted coefficients. The Random Forest classification demonstrated a high accuracy, with values of 0.97, 0.98, 0.96, and 0.97 for the LULC maps of 1985, 2000, 2015, and 2020, respectively. Croplands consistently dominated the landscape, accounting for 53.66% of the area in 1985, peaking at 67.35% in 2000, and then declining to 52.86% by 2020. Grasslands, initially the second-largest category, significantly decreased, while wetlands diminished from 14.38% in 1985 to 1.87% by 2020. Conversely, plantation forests, particularly *Acacia decurrens*, expanded from 0.4% of the area in 2000 to 28.13% by 2020, becoming the second-largest land cover type. The total ecosystem service value in the district declined from USD 219.52 million in 1985 to USD 39.23 million in 2020, primarily due to wetland degradation. However, plantation forests contributed USD 17.37 million in 2020, highlighting their significant role in restoring ecosystem services, particularly in erosion control, soil formation, nutrient recycling, climate regulation, and habitat provision. This study underscores the need for sustainable land management practices, including wetland restoration and sustainable plantation forestry, to enhance ecosystem services and ensure long-term ecological and economic sustainability.

Keywords: plantation forest; LULC change; ecosystem service values; Landsat image; northwestern Highlands

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1. Introduction

Ecosystem services refer to the various direct and indirect benefits that ecosystems provide to the overall well-being of humans [1,2]. Ecosystems provide a wide array of services that sustain life on Earth, and the magnitude of these services is contingent upon the productive capacity of the ecosystems [1,3]. Ecosystem services can be grouped as provisioning services (such as food, water, wood, medical products, and raw materials), regulating services (such as soil erosion prevention, water purification, carbon sequestration, and disease control), supporting services (such as habitat, photosynthesis, soil formation, nutrient cycling, and biodiversity conservation), and cultural services (such as aesthetic benefits, recreation, cognitive development, and spiritual enrichment) [1–4]. The first three categories directly influence human well-being in the short term, while the last one indirectly impacts human well-being in the long term by sustaining the production of other services [5,6].

Ecosystem services emanate from natural systems, contributing to human well-being through intricate interactions involving human, built, and social capitals [6]. They can be structured around payment mechanisms that supplement national revenue, thereby bolstering efforts to enhance livelihoods [7]. Expressing the values of ecosystem services in monetary terms is commonly understood by many, making it a convenient way to demonstrate the importance of natural capital alongside other forms of capital and enabling effective communication with various audiences within a specific decision-making context [6]. Quantifying and analyzing the values of ecosystem services, along with monitoring their changes, can serve as a vital tool for raising awareness [8], managing natural capital [1], and incentivizing the conservation and promotion of the ecosystems that provide higher-value services [9].

Despite the important role that ecosystem services play in maintaining natural processes and supporting sustainable livelihoods, their contribution has significantly reduced over time and across different geographical areas due to the human activities that changes in land use/land cover (LULC) are derived [10,11]. The transformation of LULC is the primary cause behind the significant changes observed in ecosystem services [11]. This transformation affects biological systems, which are crucial for facilitating essential human needs [12]. These changes illustrate the intricate connection between the evaluation of ecosystem services and various types of LULC [1,3,6,8]. Assessing the impacts of changes in LULC on the amount of ecosystem service value gained or lost is essential for indicating the vulnerability of each ecosystem service [13], thus providing valuable information for decision-making processes and understanding the status of ecosystem services [1,14,15].

In Ethiopia, the densely populated highland and midland areas are undergoing rapid population growth and concerning shifts in LULC, resulting in heightened competition for resources and subsequent encroachment upon the ecosystems of natural vegetation [8,16], followed by the land degradation associated with ecosystem conversion [17]. Land degradation is exacerbated in the northern and northwestern regions of the country due to extensive cultivation on steep slopes over many centuries, leading to severe soil erosion [18,19]. The persistent land degradation and its associated ecosystem services pose significant challenges in the northwestern Highlands [20], which account for 45% of the country's total area [21].

The northwestern Highlands of Ethiopia, characterized by diverse ecosystems ranging from montane forest to alpine meadows across rugged terrain and fertile valleys, stand as a remarkable testament to the intricate harmony of nature, crucial for both biodiversity and human sustenance, supporting ecological stability and local socio-economic well-being [22]. However, within these awe-inspiring landscapes lies a narrative of environmental fragility and human-driven pressures, casting shadows on the delicate equilibrium that underpins sustaining life in the area [23]. Rapid population growth, the expansion of agricultural land, and deforestation in the region have emerged as formidable challenges, exerting immense pressure on natural resources and ecosystem services [24]. Human activity's relentless advancement has caused the clearance of extensive forest areas, leading to soil degradation, ecosystem fragmentation, and biodiversity loss [25–27]. Such environmental deteriorations not only challenge the resilience of ecosystems but also pose a threat to the welfare of local communities who depend on these natural resources for their livelihoods and sustenance [28].

In the face of these challenges, plantation forests have emerged as a beacon of hope, offering a potential pathway towards an additional source of income and livelihood option [29,30], as well as sustainable land management and conservation [31–33]. The reduced productivity of the land, worsened by climate variability, is impacting farmers' desire to plant *Acacia decurrens* on their farmlands [34,35].

Plantation forests, characterized by the deliberate cultivation of trees for commercial and ecological purposes, have gained traction as a means to increase forest cover, promote soil conservation, provide forest products, reduce forest fragmentation, and derive the afforestation or reforestation of previously agricultural lands, which is a priority agenda for carbon sequestration and climate change mitigation [36]. The strategic establishment of these man-made forests, predominately comprising fast-growing species such as *Acacia decurrens*, holds promise for mitigating soil erosion, sequestering carbon, and providing timber resources to meet the growing demands of society [37–39]. Further, rehabilitating degraded land with plantations sustains the storage of soil and the ecosystem's carbon, lessens soil erosion, enhances soil quality, boosts overall productivity, and offers a broader range of ecosystem improvements [31,40–42].

Despite the increasing recognition of plantation forests in shaping landscape dynamics, a significant knowledge gap persists regarding their contribution to ecosystem service values within the Fagita Lekoma district, located in the northwestern Highlands of Ethiopia. Previous studies have indicated that the LULC changes in the region are primarily attributable to small-scale plantation forestry practices over the last two decades [34,43–45]. However, these investigations have largely overlooked the application of advanced machine learning techniques, which offer more robust analytical frameworks for elucidating complex ecological interactions and quantifying changes in ecosystem service values.

The establishment of plantation forests is associated with considerable changes in LULC, yet it is imperative to understand that these alterations can profoundly affect ecosystem service values. While previous research suggests that plantations can enhance biodiversity, particularly when established on degraded lands [46], there is limited empirical evidence linking these biodiversity improvements to quantifiable ecosystem services such as soil stabilization, water regulation, carbon sequestration, and habitant provision. Additionally, the role of plantation forests in increasing ecosystem service values is critical in the context of natural resource degradation, which has been prevalent in many areas, including the Fagita Lekoma district. The degradation of natural resources, due to unsustainable land use practices, deforestation, and climate change, has diminished the ecosystem service values that communities depend upon.

This study aims to address these gaps by evaluating how plantation forests can serve as a viable solution for restoring and enhancing ecosystem services, thereby compensating for the losses incurred through degradation. By comprehensively examining how plantation forests influence LULC and their implications for ecosystem service values, this study seeks to bridge the existing knowledge void. Utilizing cutting-edge remote sensing and machine learning technologies, this study explores the dynamics of LULC devoted to plantation forests and their broader effects on ecosystem services in the ecologically significant Fagita Lekoma district, which is located at the source of the Blue Nile.

Ultimately, this study aspires to provide critical insights that can guide sustainable forest management practices, contribute to the restoration of degraded landscapes, and enhance the ecosystem service values underpinning the well-being of the local population and the ecological integrity of the region. Therefore, the objective of this study is to investigate the implications of LULC changes driven by plantation forests for ecosystem service values within the study area. The quantified and spatially analyzed results will support evidence-based decision-making for sustainable land use planning, utilizing a multidisciplinary approach that integrates science, policy, and practice and sharing its findings and experiences with other localities of the country facing similar challenges.

2. Data and Methods

2.1. Study Area

This research took place in the Fagita Lekoma district, situated within the northwestern Highlands of Ethiopia. From an administrative standpoint, the district is located within the Awi Zone of the Amhara National Regional State (Figure 1). The majority of the district's topography is marked by rugged relief, with elevations ranging from 1879 m to 2922 m above sea level [47].

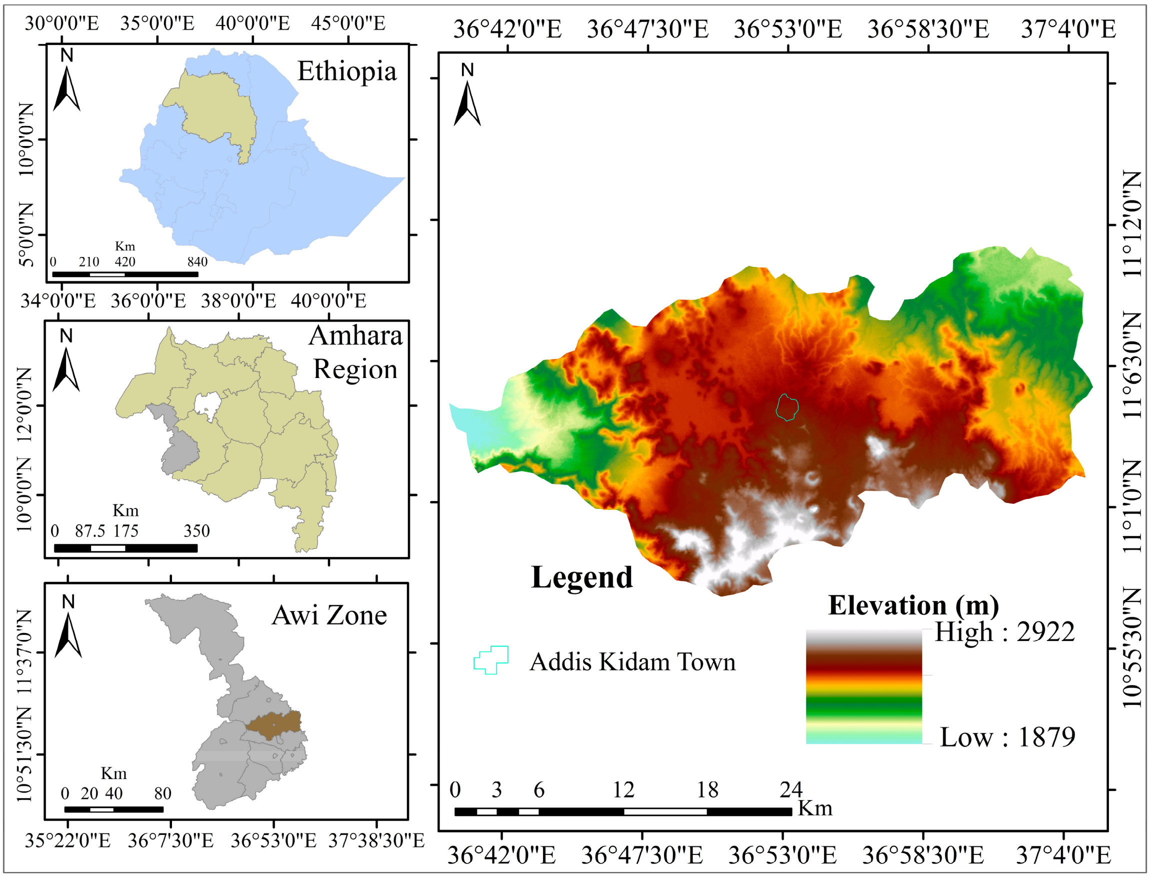

Figure 1. Map of the study area.

In the district, the average daily temperature fluctuates between 15 °C and 24 °C [42], while the annual rainfall ranges from 1500 mm to 2400 mm, with the highest precipitation levels typically occurring between June and September.

The predominant livelihood strategy among the population revolves around traditional subsistence rain-fed agriculture, encompassing a wide range of activities, such as crop cultivation and livestock husbandry [29]. Moreover, the community practices small-scale *Acacia decurrens* plantation-based farming in the area, covering 22% of the district [47], with the aim of generating income, managing soil fertility, and promoting soil and water conservation. The introduction of *Acacia decurrens* plantation forests have significantly enhanced soil properties, showing marked improvements in soil organic carbon, cation exchange capacity, soil pH, and available Bray phosphorus compared to nearby croplands [48]. This practice also provides opportunities for engaging in off-farm activities, primarily centered around seedling nursery management, charcoal production, and trading. Consequently, the vegetation status of the district has significantly improved over the last two decades, with more than 30% of the district showing positive changes that have led to notable enhancements in the ecosystem conditions [41].

2.2. Data Collection, Processing, and Classification

Satellite images from the Landsat 5 Thematic Mapper (TM) for 1985, the Landsat 7 Enhanced Thematic Mapper (ETM+) for 2000, and the Landsat 8 Operational Land Imager (OLI) for 2015 and 2020 were collected from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/, accessed on 10 February 2024) at the Level 1 stage. Each image underwent preprocessing tasks, such as radiometric and atmospheric correction, utilizing the respective ancillary data to prepare the images for generating LULC maps of the district. The selection of the year 1985 provided evidence of the LULC before the government change of 1991. The year 2000 was selected due to the availability of clear imagery over the study area. The selection of the year 2015 aimed to maintain consistency with the interval of the previous study period, while the year 2020 was chosen to assess the recent situation at the time of the proposal development. All images were acquired during February, a dry month known for the cloud-free conditions in the study area. This timing provided the optimal conditions in the study area for specifically distinguishing the LULC classes and obtaining clear satellite images of the surface.

Six LULC classes—cropland, grassland, natural forest, plantation forest, urban area and wetland—were identified in the district [34,43,45,49,50], as described in Table 1. Ground Control Points (GCPs) were collected using a combination of information from local elders, the visual interpretation of Landsat images, Global Positioning System (GPS) data for 2020, and high-resolution images from Google Earth Pro and world imagery. Additionally, personal background information about the study area was utilized. In total, 432 GCPs were gathered for 1985, 560 for 2000, 587 for 2015, and 648 for 2020. Out of the collected GCPs, 70% were allocated for training purposes, while the remaining 30% were used for testing the model results.

Table 1. Description of LULC classes in the district.

LULC	Description
Cropland	Areas cultivated for rain-fed and/or irrigation-based crops.
Grassland	Areas covered with grasses frequently grazed upon by animals.
Natural Forest	Areas covered by natural forest trees.
Plantation Forest	Areas predominantly covered by *Acacia decurrens* plantations.
Urban Area	Areas characterized by dense settlements and built-up infrastructure.
Wetland	Waterlogged areas predominantly covered by long grasses and water bodies.

The Random Forest (RF) approach, a potent machine learning classifier applicable in land remote sensing [51], was employed to derive the LULC classes for the district using the R 4.3.2 programming language. The RF algorithm outperformed other machine learning algorithms in identifying the distribution of *Acacia decurrens* plantations in the study area, with an Area Under the Receiver Operating Characteristic Curve (AUC) of 0.93 and a True Skill Statistic (TSS) of 0.82 [47]. An accuracy assessment was conducted for each LULC class using metrics including user accuracy, producer accuracy, overall accuracy, and kappa coefficient. Given their direct interpretation as probabilities that discern the data quality of a specific map, the user's accuracy, producer's accuracy, and overall accuracy were deemed the more applicable accuracy measures [52]. Thus, it was recommended to utilize all these summary measures, as relying solely on one measure may have obscured potentially important details [53]. The rate of LULC change between the study periods was determined, and the net gain or loss was quantified.

2.3. Ecosystem Service Valuation

The derived LULC classes for the years 1985, 2000, 2015, and 2020 were used to compute the ecosystem service valuation using the simple benefit transfer method. The benefit transfer method involves leveraging established values and associated data from a primary study site to estimate the ecosystem service values of comparable locations where specific valuation information is lacking [54–56]. It employs pre-existing valuation data to suit new policy frameworks [57], a practice particularly valuable when limitations in budget and time prevent the gathering of primary data [56,58].

The ecosystem service values associated with the LULC classes were determined by using coefficients developed primarily based on the methodology developed by Costanza et al. [1] and locally validated following a method performed by Kindu et al. [8] (Table 2). These coefficients have been extensively adopted by numerous scholars for estimating the ecosystem service value and analyzing its variations consequent to LULC changes within regions of limited data availability across East African countries such as Ethiopia, Kenya, Tanzania, and Malawi [59]. The methodology of equivalent coefficients involves two components: a standardized equivalent factor and an equivalent coefficients table. The standardized equivalent factor is established based on the estimated monetary value of the LULC classes, quantified in USD ha^{-1} year^{-1}. Complementarily, the equivalent coefficient table delineates the valuation weight assigned to each ecosystem service provided by various LULC classes. Consequently, the monetary estimation of a specific ecosystem service delivered by a given LULC class is computed by multiplying the standard equivalent factor with the corresponding equivalent coefficient [8,60]. Furthermore, the coefficients estimated in USD were adjusted for inflation and normalized to 2020 values using the Consumer Price Index (CPI) calculator provided by the Bureau of Labor Statistics, a division of the United States Department of Labor (https://www.calculator.net/inflation-calculator.html, accessed on 27 July 2024).

Table 2. LULC classes with their equivalent biomes, along with the coefficients representing the values of ecosystem services.

LULC Class	**Equivalent Biome**	**Ecosystem Service Value Coefficient (USD ha^{-1}yr^{-1})**	
		Global [1]	**Local [8]**
Cropland	Cropland	92	225.56
Grassland	Grass/Rangeland	232	293.25
Natural Forest	Tropical Forest	2007	986.69
Plantation Forest	Tropical Forest	2007	986.69
Urban Area	Urban	0	0
Wetland	Wetland	19580	8103.5

The ecosystem service values per unit area were estimated for each LULC class, and the total ecosystem service value for the entire district was obtained by summing the estimated values from each class and the value of each ecosystem service function derived using the following equations [61].

$$ESV_k = \sum_f A_k \times VC_{kf\_} \quad (1)$$

$$ESV_f = \sum_k A_k \times VC_{kf} \quad (2)$$

$$ESV = \sum_k \sum_f A_k \times VC_{kf} \quad (3)$$

where ESV_k, ESV_f, and ESV are the ecosystem service value of the LULC class k, the ecosystem service value of function type f, and the total ecosystem service value, respectively; A_k is the area (ha) of the LULC class k; and VC_{kf} is the value coefficient (ha^{-1}yr^{-1}) for the LULC class k with the ecosystem service function type f. The ecosystem service function coefficients for each biome are presented in Table 3.

Table 3. Coefficients of ecosystem service functions (USD $ha^{-1}yr^{-1}$) for biomes [8].

Ecosystem Service \ Biome	Cropland	Grassland	Natural Forest	Plantation Forest	Wetland
Provisioning services					
Water supply			8	8	2117
Food production	187.56	117.45	32	32	41
Raw material			51.24	51.24	
Genetic resources			41	41	
Regulating services					
Water regulation		3	6	6	5445
Water treatment		87	136	136	431.5
Erosion control		29	245	245	
Climate regulation			223	223	
Biological control	24	23			
Gas regulation		7	13.68	13.68	
Disturbance regulation			5	5	
Supporting services					
Nutrient cycling			184.4	184.4	
Pollination	14	25	7.27	7.27	
Soil formation		1	10	10	
Habitant/refugia			17.3	17.3	
Cultural services					
Recreation		0.8	4.8	4.8	69
Cultural			2	2	
Total	225.56	293.35	986.69	986.69	8103.5

The ecosystem service value changes over time were computed both in USD and as percentages, derived from the variance between the estimated values in each study period, (i), and the final (j) years, as indicated by Equation (4) [8,60].

$$Percentage\ ESV\ change = \frac{(ESV_j - ESV_i)}{ESV_i} * 100 \quad (4)$$

Sensitivity Analyses

Sensitivity analyses were undertaken to assess the impact of the variations in the applied value coefficients on the temporal change in the values of the ecosystem services, owing to uncertainties regarding the representativeness of the coefficients the proxies utilized for each LULC class [62]. In each analysis, the sensitivity coefficient was computed using the standard economic principles of elasticity, representing the percentage change in output resulting from a given percentage change in input [58]. The sensitivity coefficient of the ecosystem service values was assessed as follows [63]:

$$SC = \frac{VC_k \times A_k}{ESV} \quad (5)$$

where SC is the sensitivity coefficient, ESV is the total ecosystem service value estimated, VC is the value coefficient (USD $ha^{-1}yr^{-1}$), A is the area (ha), and k is the LULC class. In cases where $SC > 1$, the estimated ecosystem service value is identified as elastic in relation to the coefficient, emphasizing the importance of accurately defining the VC. Conversely, when $SC < 1$, the estimated ecosystem service value is considered inelastic, indicating that the results of the ESV calculations remain reliable and robust.

3. Results

3.1. Accuracy Assessment

The overall accuracy of the RF classification in this study stands impressively high, with values of 0.97, 0.98, 0.96, and 0.97 for the LULC maps of 1985, 2000, 2015, and 2020, respectively (Table 4). The minimum user's accuracy consistently surpassed 0.9 across various LULC maps over most of the study years. Particularly notable is the attainment of the full user's accuracy for urban areas in 2000, 2015, and 2020, as well as for wetlands in the 2020 LULC map. Moreover, the producer's accuracy for all LULC classes within each year's LULC maps exceeded 0.92, except for urban areas in the 2000 and 2015 LULC maps (Table 4). According to Lea and Curtis [64], an effective accuracy assessment report should feature a classification accuracy exceeding 0.9. Accuracy levels above 0.85 are deemed satisfactory for planning and management purposes [53,65]. Additionally, the Cohen's kappa value of the RF classification was 0.94, 0.97, 0.94, and 0.96 for the LULC maps of 1985, 2000, 2015, and 2020, respectively (Table 4).

Table 4. Accuracy assessment of LULC maps from 1985 to 2020.

Year / LULC	1985		2000		2015		2020	
	UA	PA	UA	PA	UA	PA	UA	PA
Cropland	0.91	0.92	0.99	0.99	0.96	0.98	0.96	0.98
Grassland	0.94	0.93	0.99	0.99	0.95	0.95	0.97	0.93
Natural Forest	0.99	0.99	0.99	0.99	0.97	0.96	0.96	0.98
Plantation Forest	-	-	0.92	0.90	0.93	0.92	0.97	0.96
Urban Area	-	-	1.00	0.6	1.00	0.81	1.00	0.99
Wetland	0.9	0.99	0.94	0.97	0.87	0.95	1.00	0.96
Overall Accuracy	0.97		0.98		0.96		0.97	
Kappa	0.94		0.97		0.94		0.96	

Note: UA is user's accuracy and PA is producer's accuracy.

3.2. LULC Changes

The landscape of the Fagita Lekoma district underwent substantial changes in LULC between 1985 and 2020 (Figures 2 and 3; Table 5). Croplands emerged as the predominant LULC class across various sectors of the district. Grasslands constituted the second most prevalent LULC category during the initial three study years, primarily concentrated in the western and the northern regions. Natural forests thrived predominantly in the higher slope areas of the southwestern escarpments of the district. The majority of wetlands within the district were situated in the central area, west of the capital town *Addis Kidam*, locally known as *Zimbiri*. Urban area expanses began to manifest in select areas of the district, spurred by the establishment of satellite towns and the expansion of *Addis Kidam* town. In the final year of the study period, 2020, plantation forests, particularly those featuring *Acacia decurrens*, witnessed a notable surge across diverse sectors of the district, eventually emerging as the second largest category after croplands.

Table 5. The extent of LULC classes in the district between 1985 and 2020.

Year / LULC	1985		2000		2015		2020	
	Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Cropland	36,204.57	53.66	45,439.56	67.35	44,518.75	65.99	35,659.87	52.86
Grassland	13,873.77	20.56	12,594.42	18.67	9574.38	14.19	7435.89	11.02
Natural Forest	7689.24	11.4	3185.19	4.72	2954.52	4.38	3193.33	4.73
Plantation Forest	_	_	273.24	0.4	6795.63	10.07	18,979.7	28.13
Urban Area	_	_	283.14	0.42	694.91	1.03	937.73	1.39
Wetland	9700.47	14.38	5692.5	8.44	2929.86	4.34	1261.53	1.87
Total	67,468.05	100	67,468.05	100	67,468.05	100	67,468.05	100

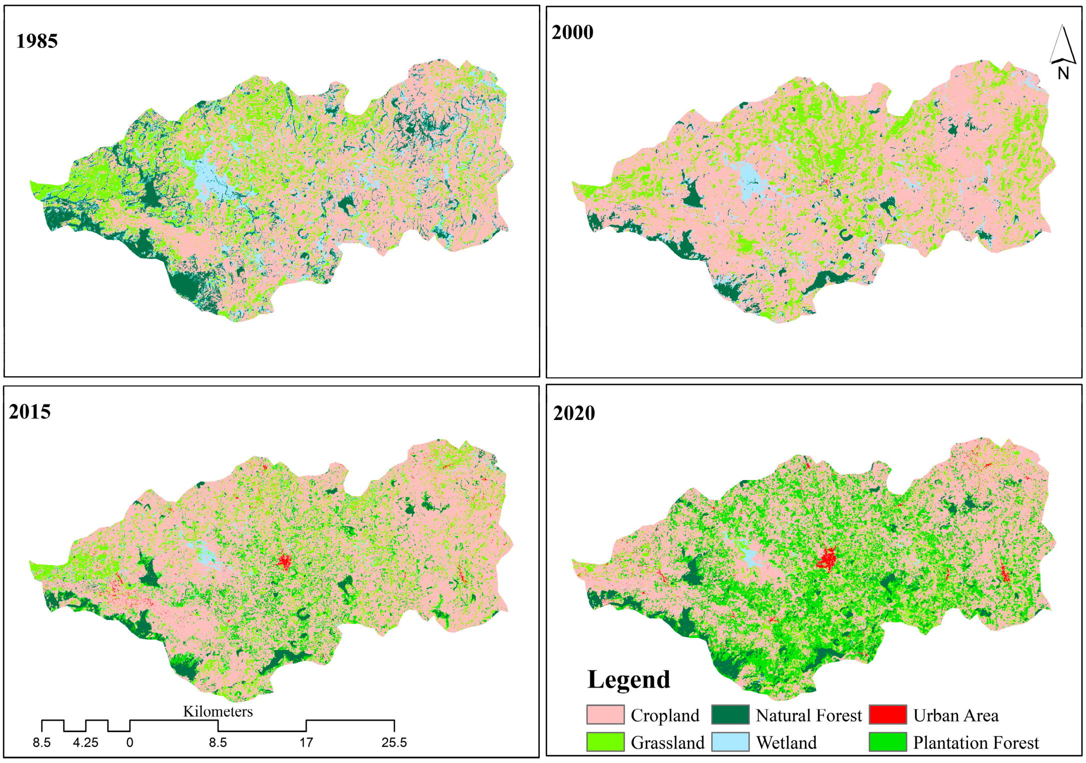

Figure 2. Spatial distribution of LULC in the Fagita Lekoma district during the 1985, 2000, 2015, and 2020 periods.

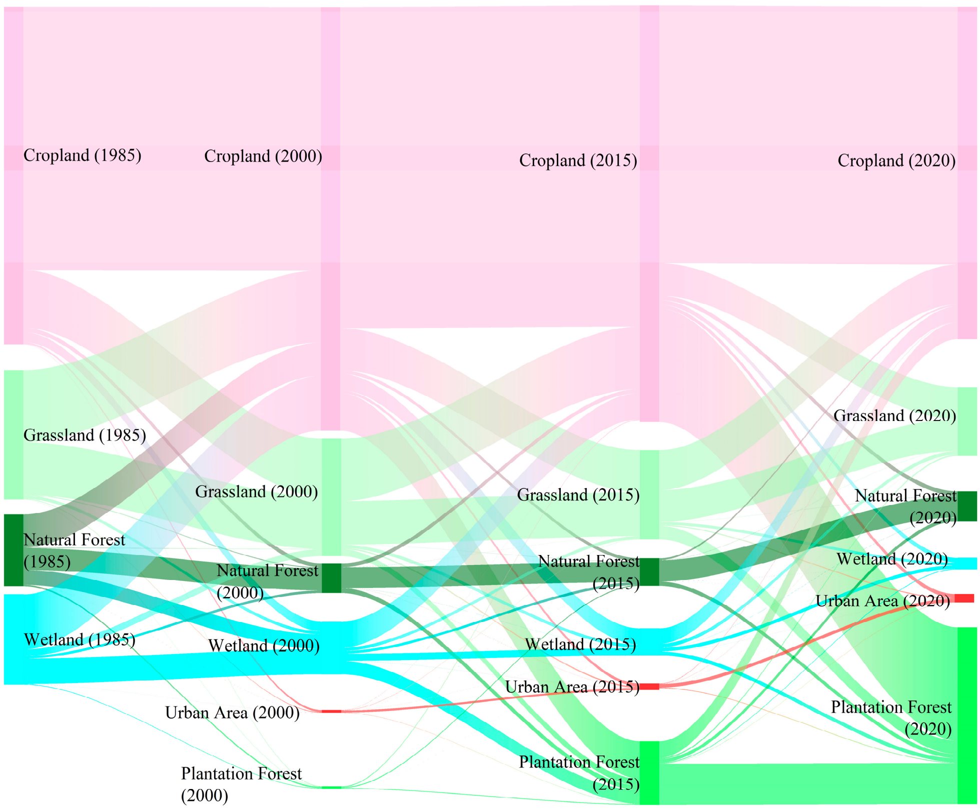

Figure 3. Transformation among LULC classes between 1985 and 2000, 2000 and 2015, and 2015 and 2020.

Throughout the LULC assessment periods, there was a consistent increase in plantation forests and urban areas, both of which were absent during the initial study year of 1985. For instance, the areas covered by plantation forests grew from 0.4% in 2000 to 10.07% in 2015 and further to 28.13% in 2020. Similarly, urban areas expanded from 0.42% in 2000 to 1.03% in 2015 and 1.39% in 2020. Croplands accounted for 53.66% of the total study area in 1985, rising to 67.35% by 2000, but then declining to 52.86% in 2020.

In contrast, wetlands and grasslands exhibited a consistent decline throughout the entire study period. Initially, wetlands encompassed 14.38% of the study area in 1985, progressively diminishing to 8.44% in 2000, 4.34% in 2015, and further to 1.87% in 2020. Similarly, grasslands decreased from 20.56% in 1985 to 18.67%, 14.19%, and 11.02 in 2000, 2015, and 2020, respectively. The extent of natural forest also experienced a reduction from 11.4% in 1985 to 4.72% and 4.38% in 2000 and 2015, respectively, with a slight recovery observed in 2020, covering 4.73%.

During the period spanning 1985 to 2000, the predominant LULC transformation was characterized by the conversion of grasslands, natural forests, and wetlands into croplands, coupled with a noteworthy transition from croplands to grasslands (Figures 2 and 3). Subsequently, from 2000 to 2015, the most notable change entailed the conversion of grasslands and wetlands to croplands, along with shifts from croplands to grasslands and plantation forests. Notably, from 2015 to 2020, a significant LULC transformation was observed, particularly the conversion of croplands to plantation forests.

3.3. Ecosystem Service Changes

According to the ecosystem service value coefficients developed for the Ethiopian Highlands, the total value of the ecosystem services in the district declined from USD 219.52 million in 1985 to USD 39.23 million in 2020 (Figures 4 and 5; Table 6). With the exception of 2020, the highest ecosystem service value is attributed to wetlands, reflecting their crucial role in providing various essential services, followed by croplands, which dominated in areal coverage throughout the study period (Figure 4). In each of the study periods, wetlands experienced a significant decline in ecosystem service values, plummeting from USD 175.34 million in 1985 to USD 64.29, 24.04, and 9.48 million in 2000, 2015, and 2020, respectively. Likewise, the ecosystem service value of the natural forest and grasslands also decreased from USD 16.92 million and USD 9.04 million to USD 2.9 million and USD 2.02 million, respectively, between 1985 and 2020. In contrast, the ecosystem service value of plantation forests, which were absent during the initial study period, surged to USD 17.37 million in 2020. Figure 3 illustrates two contrasting trends in the ecosystem service value changes between wetlands and plantation forests. While the ecosystem service value of wetlands, natural forests, grasslands, and croplands consistently decreased throughout the study period, that of plantation forests exhibited a consistent increase.

Table 6. Ecosystem service values and changes in USD million and percentages for biomes.

Biome	ESV (Million USD)				ESV Change (Million USD and %)							
					1985–2000		2000–2015		2015–2020		1985–2020	
	1985	2000	2015	2020	USD	%	USD	%	USD	%	USD	%
Cropland	18.22	14.29	10.17	7.46	−3.93	−21.57	−4.12	−28.83	−2.71	−26.65	−10.76	−59.06
Grassland	9.04	5.15	2.84	2.02	−3.89	−43.03	−2.31	−44.85	−0.82	−28.87	−7.02	−77.65
Natural	16.92	4.38	2.95	2.9	−12.54	−74.11	−1.43	−32.65	−0.05	−1.69	−14.02	−82.86
Plantation	-	0.38	6.79	17.37	0.38	_	6.41	1686.84	10.58	155.82	17.37	_
Wetland	175.34	64.29	24.04	9.48	−111.05	−63.33	−40.25	−62.61	−14.56	−60.57	−68.39	−94.59
Total	219.52	88.48	46.79	39.23	−131.04	−59.69	−41.69	−47.12	−7.56	−16.16	−56.43	−82.13

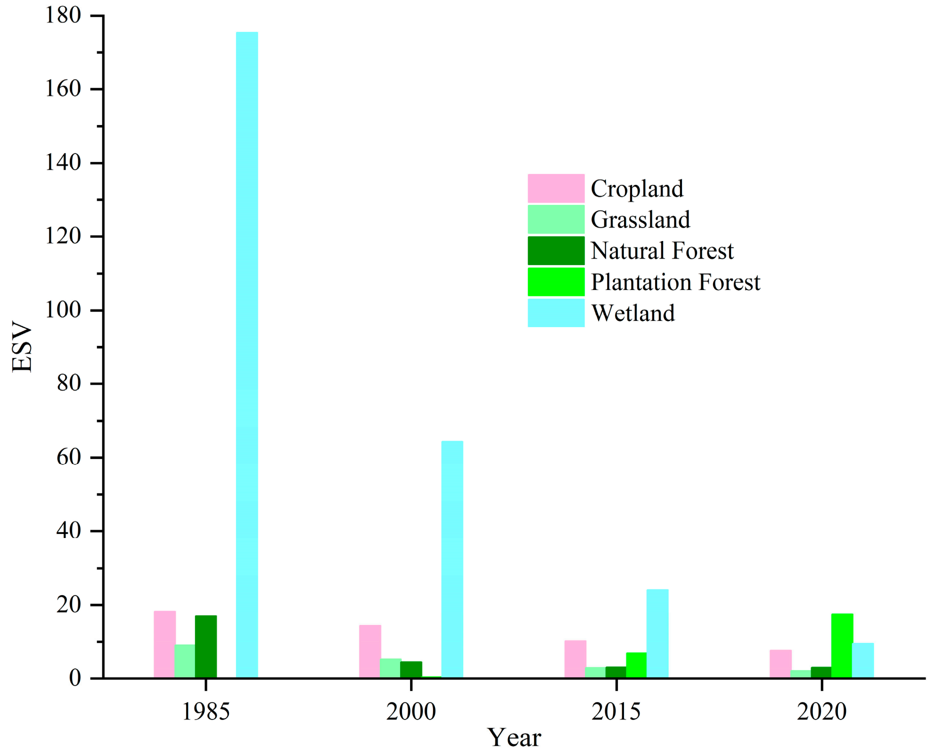

Figure 4. Ecosystem service value (ESV) in (million USD) for biomes during the study years.

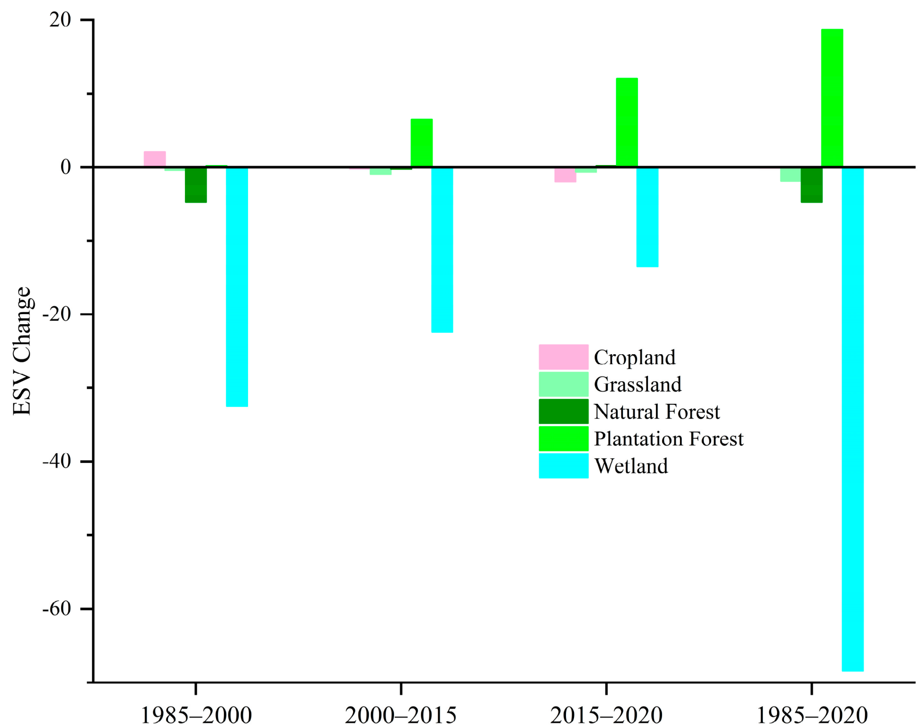

Figure 5. Ecosystem service value (ESV) changes (million USD) of biomes during the study periods.

The decline in the total ecosystem service values was primarily attributed to the loss in the provisioning, regulating, and cultural values of the ecosystem service groups (Figure 6). In contrast, the supporting service values of the study area exhibited a decline between 1985 and 2000, followed by a consistent increase in the remaining study periods. This trend was largely influenced by the pivotal role played by plantation forests in nutrient recycling, soil formation, and habitant services (Table 7).

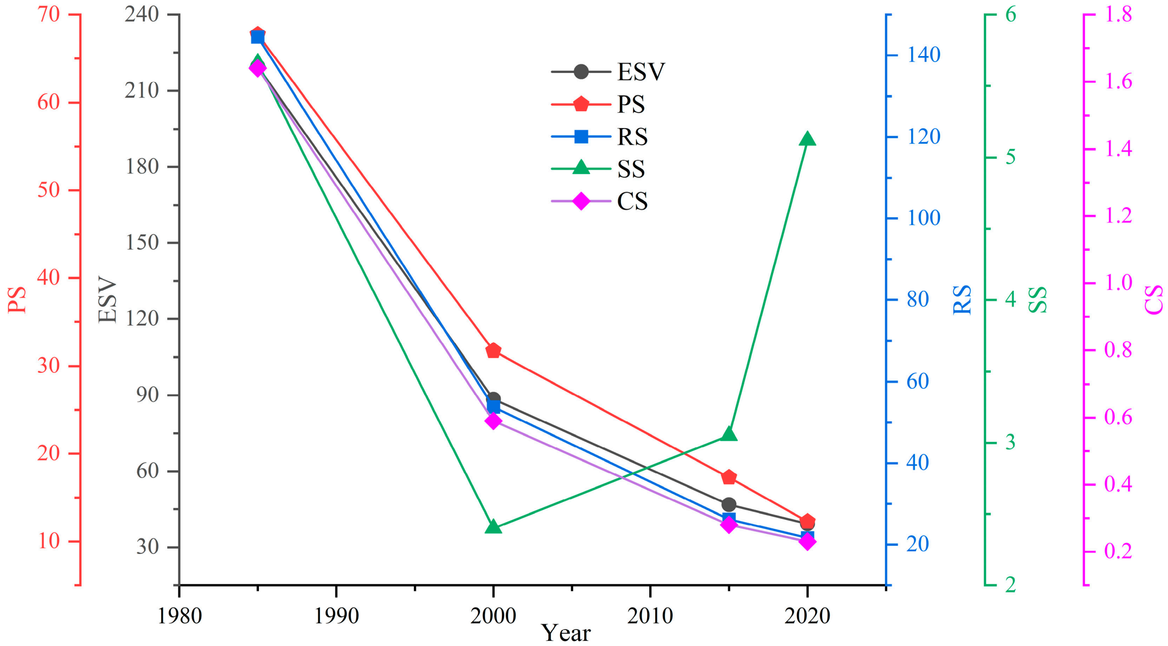

Figure 6. Temporal changes in the estimated value of grouped ecosystem service functions (million USD) between 1985 and 2020. Note: ESV is the ecosystem service value; PS is the provisioning service value; RS is the regulating service value; SS is the supporting service value; and CS is the cultural service value.

Table 7. The value of individual ecosystem service functions in USD million and percentage changes between 1985 and 2020.

Ecosystem Service	**ESV (Million USD)**				**ESV Change in %**
	1985	**2000**	**2015**	**2020**	**1985–2020**
Provisioning services	67.74	31.7	17.3	12.26	−55.48
Water supply	45.94	16.83	6.36	2.64	−43.3
Food production	20.22	14.42	10.03	7.72	−12.5
Raw material	0.88	0.25	0.51	1.05	0.17
Genetic resources	0.7	0.2	0.4	0.84	0.14
Regulating services	144.48	53.79	26.17	21.62	−122.86
Water regulation	118.01	43.28	16.24	6.51	−111.5
Water treatment	14.36	5.61	3.47	3.9	−10.46
Erosion control	5.1	1.69	2.7	5.24	0.14
Climate regulation	3.82	1.07	2.2	4.59	0.77
Biological control	2.65	1.92	1.31	0.95	−1.7
Gas regulation	0.09	0.02	0.2	0.33	−0.12
Disturbance regulation	0.04	0.02	0.05	0.1	0.01
Supporting services	5.66	2.4	3.05	5.12	−0.54
Nutrient cycling	3.16	0.89	1.82	3.79	0.63
Pollination	2.03	1.36	0.95	0.76	−1.27
Soil formation	0.17	0.07	0.11	0.21	0.04
Habitant/refugia	0.3	0.08	0.17	0.36	0.06
Cultural services	1.64	0.59	0.28	0.23	−1.41
Recreation	1.6	0.58	0.26	0.18	−1.42
Cultural	0.03	0.01	0.02	0.04	0.01
Total	219.52	88.48	46.79	39.23	−180.29

The sensitivity coefficient of the estimated ecosystem service values for all biomes across all the study years was below 0.5, except for the wetlands value, which was also less than one (Figure 7). This implies that the total estimated value of the ecosystem services within the study area exhibited a lower sensitivity compared to the modified equivalent value coefficients. Wetlands exhibited relatively higher sensitivity values, albeit with a decreasing trend. The high coefficient value of wetlands, along with their significant coverage in the study area, leads to a relatively higher dependency of ecosystem service values on them. Therefore, a small increase or decrease in wetlands can significantly impact the ecosystem service value of the study area, particularly during the first study period. Conversely, the sensitivity coefficients of grasslands and natural forests were relatively low, indicating that a small increase or decrease in these LULC classes would have a minimal effect on the ecosystem service value of the study area.

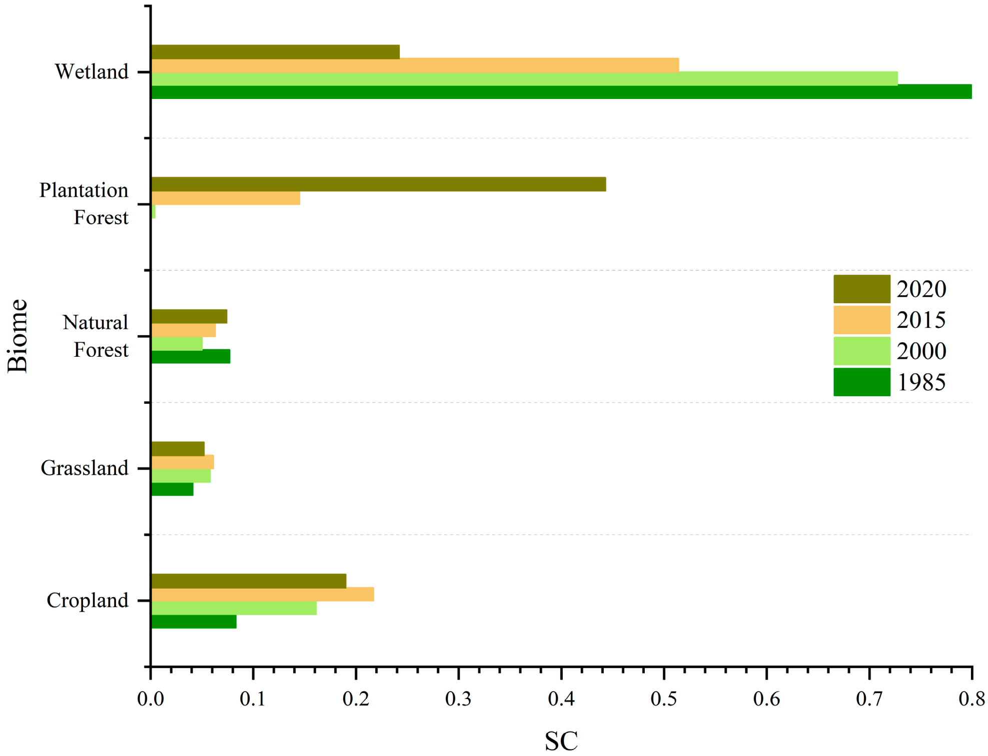

Figure 7. Sensitivity coefficient of biomes between 1985 and 2020.

4. Discussion

An estimation of the ecosystem service changes associated with changes in LULC is crucial for understanding how human activities impact the quality and quantity of these services. Conducting such estimations at local levels is vital for shaping policies that promote sustainable development, as both the ecological process and livelihoods of the community can be significantly affected by adverse LULC changes, making it essential to assess and address these impacts comprehensively [16]. Therefore, a precise assessment of the ecosystem services is essential for effective land management and the implementation of ecosystem services that support biodiversity conservation and community livelihoods.

4.1. Analysis of LULC Changes

The analysis of LULC changes in the Fagita Lekoma district from 1985 to 2020 reveals a plethora of substantial and diverse transitions occurring among different LULC classes. According to our findings, croplands were the dominant LULC class, occupying more than half of the district's area throughout the entire study period. During the first study period (1985–2000), a significant expansion of croplands was observed in the district from 56.66% to 67.35% (Table 5) at the expense of grasslands, natural forests, and wetlands (Figure 3). The findings, consistent with numerous prior studies conducted across the country at district and watershed levels, reveal significant LULC transformations, predominantly characterized by the encroachment of cropland areas at the expense of grasslands, natural vegetations, wetlands, and shrublands, particularly within highland areas [45,66–69]. This change is primarily driven by anthropogenic activities, including population growth, and is compounded by the effects of climate change [70,71]. The dominance of croplands, which have emerged as the main LULC class, reflects a larger pattern seen not only in Ethiopia but also in in other regions worldwide, where agricultural expansion significantly shapes LULC changes over time [72,73].

However, during the study periods of 2000–2015 and 2015–2020, there was a decline in the extent of croplands, which coincided with the establishment of plantation forests in the district (Figure 3). Similar results were observed in the northwestern Highlands of Ethiopia, attributed to diminished crop productivity resulting from severe soil erosion and land degradation [20,74]. Crop production and productivity in these areas were severely constrained by high soil acidity and extensive leaching [75,76]. To mitigate these issues, farmers experimented with strategies, including implementing significant LULC changes through the establishment of plantations [29,33,34,43]. As a result, there was a significant increase in plantation forests, particularly *Acacia decurrens*, during the latter part of the study period.

The coverage of plantation forests grew from nothing in 1985 to 28.13% in 2020 (Table 5). Similar findings were reported for the study area, indicating plantation-induced changes in forest cover. For instance, Wondie and Mekuria [43] reported an annual increase in forest cover of 1.2% in the district between 1995 and 2015, primarily attributed to the increased planting of *Acacia decurrens*. Worku et al. [49] also noted that between 2000 and 2017, plantation forests, mainly due to *Acacia decurrens*, were the most expanded LULC class in the district, increasing by 16% and contributing to the rehabilitation of degraded mountainous areas by reducing soil erosion. Furthermore, Alemayehu et al. [47] used high-resolution earth observation data and machine learning methods to identify the spatial distribution of *Acacia decurrens* plantations in the district, finding that 22.44% of the district is covered by this species.

Grasslands, initially the second most prevalent LULC category, declined by half between 1985 and 2020 (Table 5). Yimam et al. [77] reported similar findings in the north-western Highlands, which share ecological characteristics with the study area, noting a decrease in grazing land between 1991 and 2023. Additionally, a study by Kuma et al. [78] in the southern part of the country indicated a 3.18% decrease in this LULC type between 1986 and 2018.

Natural forests also showed a significant decline from 11.4% in 1985 to 4.38% in 2015. This deforestation trend aligns with global patterns, where forests are increasingly cleared for agriculture and other anthropogenic activities [79]. Deforestation in Ethiopia is often linked to the expansion of smallholder farms and the demand for fuelwood [80], highlighting the complex socio-economic factors driving these changes. The slight recovery observed during the last study period, from 2015 to 2020 (Table 5), can be attributed to the expansion of plantation forests, which have helped to reduce the pressure on natural forests for various purposes such as fuelwood.

Wetlands experienced a dramatic reduction from 14.38% in 1985 to 1.87% in 2020 (Figure 3). This result is consistent with the findings of Assefa et al. [81], who reported that wetlands and water bodies decreased by 75.71% in the peri-urban areas of Bahir Dar town, located within a 100 km radius of our study area between 1994 and 2019. Wetlands are the most dynamic of all the observed LULC classes in the Choke watershed, showing a significant reduction from 946.3 km^2 in 1986 to 111.5 km^2 in 2005 [82]. Further, another study by [83] revealed that 98% of wetlands in southwestern Ethiopia were lost between 1992 and 2022. The LULC transformation results (Figure 3) show that during the study period, nearly all changes in wetlands were due to conversion to croplands. A significant portion of wetland decline, 69.9%, can be attributed to the expansion of cropland in the Burie Womberma district of the northwestern Highlands of Ethiopia [84]. This result aligns with global studies indicating that the loss of wetland areas has been accelerating in recent centuries [85]. The degradation of wetlands is a critical environmental concern, reflecting a global trend of wetland loss due to land conversion, climate change, and drainage for agriculture [86]. The increase in population and the fortunate possibility of alternative livelihood options have led to the conversion of wetlands into croplands, while soil erosion, sediment deposits from the degradation of wetland buffers, and overgrazing have further exacerbated wetland loss [84].

Urban areas of the district exhibited a consistent increase, notably characterized by the expansion of Addis Kidam town and the establishment of satellite towns such as Fagita, Chiguali, and Gezehera. This trend of urbanization mirrors the rapid urban growth observed not only in Ethiopia but also in other developing countries, driven by population growth and economic development [87]. The majority of the urban area expansion comes at the expense of croplands (Figure 3), with the growth of urban areas often leading to the conversion of croplands and natural landscapes, thereby exacerbating LULC changes, as well as environmental degradation [88].

4.2. Implications of LULC Changes for Ecosystem Service Values

The changes in ecosystem service values from 1985 to 2020 in the study area reveal significant shifts in the LULC and ecosystem conditions. The decline in the total ecosystem service value from USD 219.52 million in 1985 to USD 39.23 million in 2020 highlights the profound impact of human activities and environmental changes on ecosystem functions and services.

The most notable decline was observed in wetland ecosystems, which were the most dominant in terms of ecosystem service value. Their value plummeted from USD 175.34 million in 1985 to USD 9.48 million in 2020. This result is consistent with the findings from a study on the southwestern Highlands of Ethiopia, where wetlands, the main LULC class contributing to the ecosystem service values in 1986, had declined by 2019, with croplands overtaking their position [89]. Similar results were reported by Tolessa et al. [90], who found that wetlands had the highest ecosystem service value in 1987 but saw a reduction by 2019, with croplands taking their place in the Fincha watershed, located in the northwestern Highlands of Ethiopia.

The dramatic reduction can be attributed to several interrelated factors. LULC change, where wetlands have been transformed into croplands and grasslands (Figure 3), has led to a significant loss of the ecosystem services traditionally provided by wetlands. The overexploitation of wetland resources and pollution have further degraded these ecosystems, diminishing their capacity to provide essential services such as water purification, flood control, and biodiversity habitats. In line with this, Tareke [91] identified that the degradation of wetlands in the Geray wetland, located in the northwestern Highlands of Ethiopia, was driven by the expansion of uncontrolled irrigation and sedimentation, influenced by high population pressure, weak institutional performance, and the lack of ownership, which are the drivers that result in the degradation of wetlands in the Geray wetland in the northwestern Highlands of Ethiopia.

Natural forests also experienced a decline in their ecosystem service values, decreasing from USD 16.92 million in 1985 to USD 4.38 million in 2000, and further to USD 2.95 million in 2015 and USD 2.9 million in 2020. A recent study in the Sinan district, located in the northwestern Highlands of Ethiopia, showed a similar pattern in the ecosystem service value of natural forests, decreasing from USD 2.04 million in 1993 to USD 0.96 million in 2004 and further to USD 0.68 million in 2014 [77]. Additionally, the ecoservice value of grasslands consistently declined throughout the study period (Figure 4 and Table 6). The total loss of the ecosystem service value in the northeastern Highlands of Ethiopia was significant, decreasing by 67.3% from USD 80.3 million in 1984 to USD 26.4 million in 2021, primarily due to the reduction in wetlands, forests, and grasslands [92]. Furthermore, these findings align with the global studies of Sannigrahi [93], which reported significant annual losses in the ecosystem service value for wetlands (USD 1081.88 billion), forests (USD 165.89 billion), and grasslands (USD 89.01 billion) between 1995 and 2015, identifying them as the most extensively affected LULC classes.

In contrast to the declines observed in wetlands, natural forests, croplands, and grasslands, the establishment and growth of plantation forests present a positive trend. The ecosystem service value of plantation forests increased significantly to USD 17.37 million by 2020, making it the highest among all biomes, despite being absent in 1985. Without wetlands, the total ecosystem service value of the district experienced a slight decline, decreasing from USD 24.2 million in 2000 to USD 22.75 million in 2015 following the introduction of plantation forestry practices. However, it rebounded to USD 29.75 million by 2020. This indicates that the positive impact of plantation forests on the district's ecosystem service value was significantly overshadowed by the dramatic decline in wetlands. This is confirmed by the study on the Guder watershed, covering the eastern part of the district where wetlands were rare, which showed the total ecosystem service value decreased from USD 192.4 thousand in 1982 to USD 131.8 thousand in 2006, but then increased to USD 202.4 thousand in 2017, clearly indicating that the lost contribution of forests to the total ecosystem service value was replaced by plantation forests, specifically *Acacia decurrens* plantations [44]. A similar trend of ecosystem service value changes, with a decrease from USD 224.61 million in 1984 to USD 155.85 million in 1998, followed by an increase to USD 229.15 million in 2013 and further to USD 251.59 million in 2021, was reported by Debie and Anteneh [20] about the Gilgel Abay watershed, attributed to the expansion of plantation forests, specifically *Acacia decurrens* (around our study area) and Eucalyptus (around the Mecha district). This positive trend aligns with the findings of Paquette and Messier [94], which emphasized the potential of plantation forests to deliver ecosystem services, especially in degraded landscapes. It is essential to manage plantation forests sustainably to ensure they complement, rather than replace, natural forests, which offer a broader range of ecosystem services. While plantation forests can help mitigate the impacts of deforestation and land degradation, they should support the conservation of ecosystem services. In this study, the use of similar coefficients for both plantation and natural forests in ecosystem service valuations is not due to their equal contributions, but rather the lack of field-based quantified measurements. Plantation forests often differ from natural forests in regeneration, species diversity, ecosystem functioning, and the services they provide, especially in their early stages. Over time, the ecosystem services offered by planted forests can, in some cases, become comparable to those of natural forests [95]. Although natural forests deliver superior ecosystem services compared to plantations, plantation forests still play a vital role by providing clean air, protecting water resources, and offering a variety of services, including the production of woody and non-woody products, soil erosion control, climate regulation, carbon sequestration, biodiversity conservation, and aesthetic benefits [96].

The decline in the total ecosystem service values was primarily attributed to the loss in the provisioning, regulating, and cultural values of the ecosystem service groups. Provisioning services, encompassing vital functions such as water supply, are impacted by the reduction in wetlands, natural forests, and grasslands, while food production is affected by the relative decrease in croplands. Specifically, the decline in the food production of the district after 2000 was related to the decrease in the extent of croplands, due to the conversion of LULC to *Acacia decurrens* plantations. This result aligns with the findings of [77], which emphasized that the expansion of plantations negatively impacted the specific ecosystem service values of food production in the Upper Blue Nile basin. The replacement of croplands with plantations directly impacts farmers' livelihoods by raising food costs, which, in turn, increase production expenses and the prices of agricultural products in local markets [35]. Conversely, Bazie et al. [31] indicated that the shift from cereal-based farming to *Acacia decurrens*-based farming by smallholder farmers could enhance soil fertility and health, ultimately leading to increased crop productivity in the long term. Regulating services, such as water regulation and treatment, exhibited a decline mainly due to the degradation of wetlands and natural forests. The decrease in specific natural biomes, such as wetlands and natural forests, could have a profound impact on essential ecosystem services, such as water regulation [90,97]. However, other specific functions such as erosion control and climate regulation improved due to the expansion of plantation forests. Locally embraced agroforestry techniques have the potential to elevate soil properties and nutrient content over an extended period, thus playing a pivotal role in bolstering soil fertility and advancing climate change mitigation efforts through carbon sequestration [98,99]. Plantation forests offer vital ecosystem services, including water purification, hydrological regulation, carbon sequestration, enhanced biodiversity connectivity, and desertification mitigation, with their importance expected to increase in the future [100].

Further, the supporting service values of the study area exhibited a decline between 1985 and 2000, followed by a consistent increase in the remaining study periods. This trend was largely influenced by the pivotal role played by plantation forests in nutrient recycling, soil formation, and habitant services. Plantation-based agriculture consistently reduced runoff and erosion, improved carbon sequestration, and uniquely reduced nutrient leaching, while organic amendments and conservation tillage enhanced water holding capacity [101]. The contribution of plantation forests to enhance these supporting services and some elements of the regulating services, fundamental for maintaining other types of ecosystem services, underscores their importance in the landscape.

4.3. Implications for Ecosystem Management

The contrasting trends between the decline in wetland, natural forest, and grassland services and the rise in plantation forest services highlight several critical points for ecosystem management. There is a clear need for sustainable land use practices that balance agricultural development with the conservation of natural ecosystems. Integral land management approaches that consider the multifunctionality of landscapes can help achieve this balance, ensuring that LULC changes do not compromise the provision of essential ecosystem services.

Investment in restoration projects for degraded wetlands could help recover ecosystem services. Restoration efforts should focus on enhancing the ecological integrity of and resilience of the ecosystems, promoting biodiversity conservation, and improving the livelihoods of local communities. Policymakers and land managers must prioritize conservation and restoration efforts, integrating them into broader land use planning and sustainable development strategies.

While plantation forests can provide valuable ecosystem services, it is essential to ensure they are managed sustainably and to carefully consider their potential negative environmental impacts. Sustainable management practices, such as mixed-species plantations and agroforestry systems, can enhance the ecological and economic benefits of plantation forests, contributing to long-term sustainability and resilience.

4.4. Limitations of This Study

The estimation of changes in ESVs in this study was facilitated by utilizing LULC datasets. However, the Landsat 7 images in the study area for the years around 2010 exhibited striping, necessitating the use of study periods with different intervals. The LULC classes in the study area were identified with a relatively high accuracy, adopting machine learning algorithms, but it would be preferable to utilize data with relatively higher spatial resolutions for a better estimation of the ecosystem service values. The ecosystem service value coefficients for this study were adopted from Kindu et al. [8], where different biomes were assigned the same value. For instance, both natural forests and plantation forests are represented by the same value, which may have differences on some individual ecosystem service function values in reality. Moreover, the types of plantation forests vary, and their implications for ecosystem services differ accordingly. Given the financial constraints affecting the collection of primary data in developing nations, this study adopted the modified ecosystem service values model developed by Kindu et al. [8] for the Ethiopian Highlands context, which is the most feasible option available with the limitations. Furthermore, considering the expansion of *Acacia decurrens* plantation forests in the northwestern Highlands of the country, it would be beneficial to establish its ecosystem service valuation coefficients based on direct field measurements.

5. Conclusions

The analysis of LULC changes in the Fagita Lekoma district spanning from 1985 to 2020 reveals a significant transformation driven by human activities. These changes have had profound repercussions on ecosystem services, which have notably witnessed declines in wetlands, natural forests, and grasslands, while the establishment of plantation forests presents a positive trend.

The evident decline in ecosystem service values, particularly in wetlands, underscores the pressing need for sustainable land management practices. Restoration initiatives targeting degraded wetlands hold promise for restoring ecosystem services, fostering biodiversity conservation, and enhancing local livelihoods. Such endeavors should be seamlessly integrated into broader land use planning frameworks and sustainable development strategies to ensure long-term effectiveness.

Although plantation forests provide valuable ecosystem services that help offset the decline in the ecosystem service values caused by natural biome degradation, their management requires careful consideration to ensure their sustainability and mitigate potential adverse environmental impacts. Embracing sustainable practices like mixed-species plantations and agroforestry systems can amplify the ecological and economic benefits of plantation forests, thus safeguarding their long-term sustainability and resilience.

In essence, effective ecosystem management necessitates a holistic approach that acknowledges the multifaceted nature of landscapes. It should prioritize the conservation of natural biomes alongside agricultural and urban development, while promoting the planting of economically important and environmentally friendly species. Through the adoption of integrated land management strategies and proactive investments in restoration and sustainable practices, policymakers and land managers can navigate the challenges posed by LULC changes while fostering resilient ecosystems for future generations.

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