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Role of Forest Ecosystems in Climate Regulation and Disaster Risk Reduction in Dawro Zone, South West Ethiopia

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ABSTRACT

Forest ecosystems play a critical role in climate regulation and disaster risk reduction (DRR), particularly in mountainous regions that are highly vulnerable to climate-induced hazards. This study evaluates the contribution of forest ecosystems to carbon sequestration, microclimate regulation, and mitigation of floods and landslides in Dawro Zone, South West Ethiopia. A mixed-methods approach was employed, integrating multitemporal remote sensing analysis (2000–2020), field-based forest biomass and carbon stock assessment, microclimate monitoring, and socioinstitutional surveys. Forest cover change was analyzed using Landsat imagery, achieving an overall classification accuracy of 89.3% ($\kappa = 0.86$). Aboveground biomass was estimated using the Brown (1997) allometric equation, and carbon stocks were derived using a carbon fraction of 0.47 with associated uncertainty estimates. Results indicate that natural moist forests store significantly higher carbon stocks ($84.84 \pm 8.79\ t\,C\ ha^{-1}$) than plantation forests ($65.94 \pm 7.14\ t\,C\ ha^{-1}$), agroforestry systems ($46.34 \pm 5.36\ t\,C\ ha^{-1}$), and degraded forests ($35.44 \pm 4.51\ t\,C\ ha^{-1}$). Microclimate observations show that intact forests reduce air temperature by up to 7.2°C, enhance relative humidity, and increase soil moisture compared to degraded landscapes. Spatial and statistical analyses reveal a strong inverse relationship between forest cover and disaster occurrence, with higher forested areas experiencing significantly fewer flood and landslide events ($r = -0.87$ for floods; $r = -0.81$ for landslides; $p < 0.01$). Remote sensing results further indicate a 27.6% decline in natural forest cover between 2000 and 2020, largely driven by agricultural expansion. Community surveys show high local awareness of forest-based climate and disaster buffering functions, while institutional analysis reveals gaps in coordination between forestry and disaster management sectors. The study concludes that forest ecosystems in Dawro Zone function as natural infrastructure for climate regulation and DRR. Integrating forest conservation, restoration, and ecosystem-based disaster risk reduction (Eco-DRR) into regional development and climate adaptation policies is essential for enhancing landscape resilience and sustaining ecosystem services.

1 | Introduction

Forest ecosystems are increasingly recognized as critical natural infrastructure for climate regulation and disaster risk reduction (DRR), particularly in mountainous and environmentally fragile regions. Through carbon sequestration, regulation of local and regional climates, and stabilization of soils and hydrological processes, forests play a central role in mitigating climate change impacts and reducing vulnerability to climate-related hazards such as floods, landslides, and soil erosion [1–4]. As the frequency and intensity of extreme climatic events increase globally, the integration of forest ecosystem services into climate adaptation and disaster risk management strategies has become a key policy priority under nature-based solutions and ecosystem-based disaster risk reduction (Eco-DRR) frameworks [5, 6].

In mountainous landscapes, forests influence disaster dynamics by intercepting rainfall, enhancing infiltration, reinforcing slope stability through root systems, and reducing surface runoff. Numerous studies have shown that deforestation and forest degradation significantly increase the likelihood and severity of floods and landslides, while intact forest cover can substantially reduce hazard exposure and disaster losses [7–9]. Beyond physical protection, forests also regulate microclimatic conditions by moderating air and soil temperatures, increasing atmospheric humidity, and conserving soil moisture, thereby buffering ecosystems and livelihoods against climate variability and extremes [10, 11].

Ethiopia is particularly vulnerable to climate change and disaster risks due to its rugged topography, high rainfall variability, land degradation, and strong dependence on rain-fed agriculture. The Ethiopian highlands, including the southwestern mountainous regions, experience recurrent floods, landslides, and soil erosion, which are often exacerbated by deforestation, agricultural expansion, and weak land-use planning [12, 13]. In this context, forests play a dual role: They serve as major terrestrial carbon sinks supporting national climate mitigation efforts, and they act as protective buffers that reduce exposure and sensitivity to climate-induced hazards.

Dawro Zone, located in the southwestern highlands of Ethiopia, represents a landscape where these interactions between forests, climate regulation, and disaster risk are particularly pronounced. The zone hosts remnant moist montane and riparian forests embedded within a matrix of agricultural land, plantations, and degraded areas. These forests support local livelihoods through timber, nontimber forest products, and ecosystem services, while also stabilizing steep slopes and regulating hydrological flows. However, rapid population growth, agricultural expansion, plantation establishment, and unsustainable resource extraction have resulted in substantial forest cover loss over recent decades, raising concerns about declining ecosystem services and increasing disaster vulnerability.

Despite growing policy attention to ecosystem-based adaptation and Eco-DRR at global and national levels, empirical evidence linking forest ecosystem condition to climate regulation and disaster risk reduction at subregional and local scales in Ethiopia remains limited. Existing studies often focus either on forest cover change or on disaster impacts in isolation, with relatively few integrating biophysical measurements (such as biomass, carbon stocks, and microclimate) with spatial hazard analysis and socioinstitutional perspectives. Moreover, inconsistencies in methodological reporting—particularly regarding biomass estimation, uncertainty, and causal interpretation of forest–disaster relationships—have constrained the application of research findings in policy and planning contexts.

In addition, forest governance in Ethiopia is characterized by fragmented institutional mandates and limited coordination between forestry, climate change, and disaster risk management sectors. While community-based forest management practices and indigenous knowledge systems—such as sacred groves and customary forest protection rules—remain important in regions such as Dawro, these systems are increasingly challenged by socioeconomic pressures and weak institutional support [14]. Understanding how ecological functions, community perceptions, and institutional arrangements interact is therefore essential for designing effective and context-specific forest-based DRR strategies [15].

Against this background, the present study aims to provide an integrated assessment of the role of forest ecosystems in climate regulation and DRR in Dawro Zone, South West Ethiopia. By combining multitemporal remote sensing analysis (2000–2020), field-based forest biomass and carbon stock estimation, microclimate monitoring, and socioinstitutional surveys, the study seeks to generate robust, locally grounded evidence on how different forest types contribute to climate mitigation, microclimatic buffering, and hazard reduction. Particular attention is given to methodological transparency, uncertainty reporting, and the avoidance of simplistic causal claims by explicitly accounting for biophysical and spatial confounding factors.

By situating the findings within the broader literature on Eco-DRR, restoration opportunities, and nature-based solutions, this research aims to bridge the gap between ecological science and disaster risk management practice [16]. The results are intended to inform regional development planning, climate adaptation strategies, and forest governance reforms, highlighting the importance of conserving and restoring native forest ecosystems as cost-effective and multifunctional solutions for enhancing resilience in Ethiopia's mountainous landscapes [17].

In doing so, this study underscores the need for a coordinated effort between government institutions, local communities, and development partners to promote forest-based strategies that safeguard both people and the environment.

1.1 | Objectives of the Study

1.1.1 | General Objective

- ❖ To evaluate the role of forest ecosystems in climate regulation and DRR in the mountainous regions of Dawro Zone, South West Ethiopia.

1.1.2 | Specific Objectives

- ❖ To assess the current status and trends of forest cover in Dawro Zone using remote sensing and GIS techniques.
- ❖ To estimate the carbon sequestration potential of different forest types in the study area.
- ❖ To examine the role of forest ecosystems in mitigating climate variability and regulating local microclimates.
- ❖ To analyze the contribution of forest cover in reducing the risk and impacts of natural disasters such as landslides, floods, and soil erosion.
- ❖ To explore local communities' perceptions and knowledge regarding the role of forests in DRR and climate regulation.
- ❖ To provide evidence-based recommendations for integrating forest ecosystem services into climate adaptation and disaster risk management policies in Dawro Zone.

2 | Materials and Methods

2.1 | Study Area

The study was conducted in Dawro Zone, located in the southwestern highlands of Ethiopia within the South West Ethiopian Peoples' Regional State (SWEP). The zone lies between 6°36′–7°21′ N latitude and 36°52′–37°52′ E longitude, with elevations ranging from approximately 1200 to 2,800 m a.s.l. The terrain is predominantly mountainous and dissected by deep valleys, making the area highly susceptible to soil erosion, landslides, and flash floods.

The climate of Dawro Zone is humid to subhumid, with mean annual rainfall ranging from 1400 to 2200 mm, concentrated mainly between May and October. Mean annual temperatures vary from 15 to 22°C depending on altitude. The zone contains remnant moist montane forests and riparian forests, plantation forests (mainly *Eucalyptus camaldulensis* and *Cupressus lusitanica*), agroforestry systems, and degraded lands. Agriculture is the dominant livelihood activity, and dependence on forest ecosystem services is high. Figure 1 shows the map of Dawro Zone.

2.2 | Research Design

A mixed-methods research design was employed to capture the biophysical, spatial, and socioinstitutional dimensions of forest ecosystem services related to climate regulation and DRR. The design integrates the following:

- Remote sensing and GIS analysis to assess forest cover dynamics and spatial relationships with hazard occurrence;
- Field-based ecological measurements to quantify forest biomass, carbon stocks, and microclimate regulation;
- Socioinstitutional surveys and interviews to capture community perceptions and governance aspects related to forest-based DRR.

This integrated approach allows triangulation of evidence and reduces reliance on single-method inference, thereby strengthening the robustness of conclusions.

2.2.1 | Forest Sampling Design and Plot Establishment

Forest biomass and microclimate data were collected using a stratified random sampling approach. Stratification was based on forest type, altitudinal range, and disturbance intensity. Four major land-use/forest categories were considered: natural moist forest, plantation forest, agroforestry systems, and degraded forest.

A total of 72 square plots (20 m × 20 m; 0.04 ha) were established across three woredas (Essera, Mareka, and Tocha): Natural forest: 30 plots, plantation forest: 18 plots, agroforestry systems: 12 plots, and degraded forest: 12 plots.

Plots were spaced at least 200 m apart to ensure spatial independence. Within each plot, all live trees with DBH ≥ 10 cm were measured.

2.3 | Tree Measurement and Aboveground Biomass (AGB) Estimation

For each sampled tree, diameter at breast height (DBH) was measured at 1.3 m above ground using a diameter tape. Tree height was measured for a representative subset of individuals using a clinometer to characterize stand structure.

AGB was estimated using the widely applied Brown [18] allometric equation for moist tropical forests:

$$\mathrm{AGB}(kg) = \exp(-2.134 + 2.530\ln(D)), \tag{1}$$

where

- AGB = aboveground biomass of an individual tree (kg)
- D = diameter at breast height (DBH) in centimeters (cm)
- ln = natural logarithm

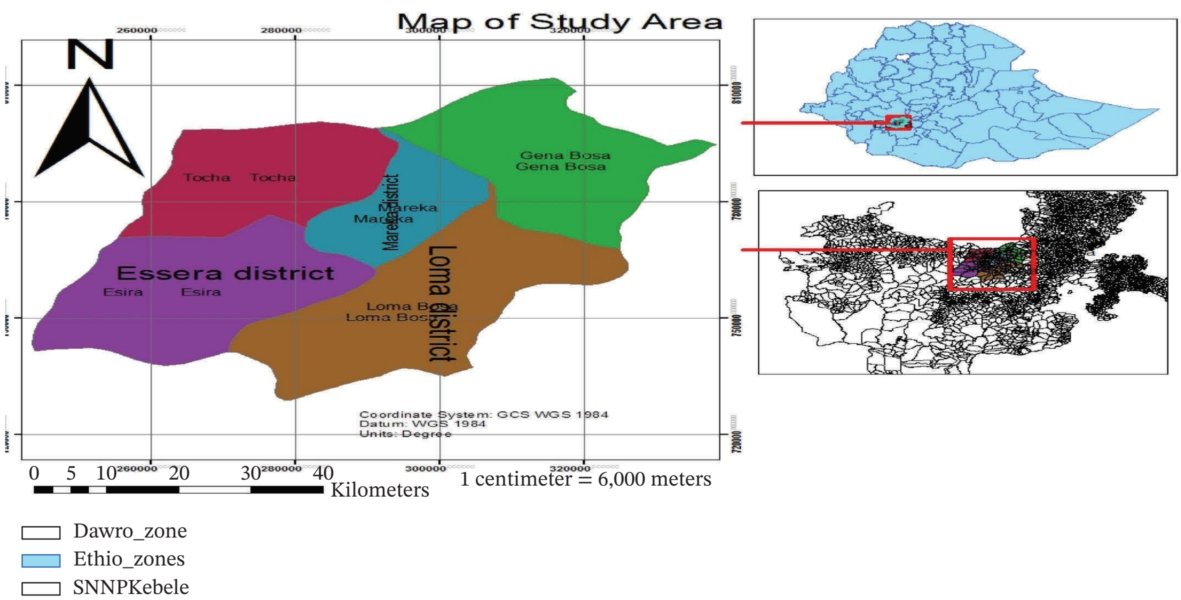

FIGURE 1 | Map of Dawro Zone.

- exp = exponential function

Plot-level biomass was calculated by summing tree biomass values and converting them to tons per hectare (t ha−1).

2.4 | Carbon Stock Estimation and Uncertainty Analysis

Aboveground carbon stock (AGC) was calculated by multiplying AGB by a carbon fraction of 0.5, following IPCC [19]:

The AGC was calculated using the following formula:

$$AGC = AGB \times 0.5, \quad (2)$$

where

- AGC = aboveground carbon stock (kg or $t\,ha^{-1}$)
- AGB = aboveground biomass (kg or $t\,ha^{-1}$)
- 0.5 = carbon fraction of dry biomass, as recommended by IPCC [19].

Carbon stock (t C ha−1) is calculated as follows.

The methodological description in the carbon stock estimation section has been revised to explicitly state the use of a 0.5 carbon fraction for woody biomass, consistent with IPCC [19] guidelines.

Uncertainty was quantified by calculating 95% confidence intervals using plot-level variance within each forest type. This approach captures variability arising from forest structure differences and sampling error and allows transparent comparison across land-use categories.

2.5 | Microclimate Data Collection

Microclimatic variables were measured to assess the climate regulation function of different forest types. Data were collected using HOBO MX2301 temperature–relative humidity data loggers and Decagon GS3 soil sensors.

- Air temperature and relative humidity were recorded at 1.5 m above ground.
- Soil temperature and volumetric soil moisture were recorded at 10 cm soil depth.
- Sensors were programmed to record data at 30-min intervals.

A total of 24 microclimate monitoring stations were installed (six per forest type). Measurements were conducted continuously for 12 months, covering both wet and dry seasons.

2.6 | Remote Sensing Data and Image Processing

Multitemporal Landsat imagery (Landsat 7 ETM+ and Landsat 8 OLI) covering the period 2000–2020 was acquired from the USGS archive and processed using Google Earth Engine (GEE) and QGIS.

Image preprocessing included the following:

- Cloud and cloud-shadow masking using the CFMask algorithm,
- Correction of Landsat 7 SLC-off gaps through multitemporal compositing,
- Radiometric and geometric normalization.

Supervised land use/land cover classification was conducted using the maximum likelihood algorithm, categorizing the landscape into natural forest, plantation forest, agricultural land, and degraded/bare land.

2.7 | Classification Accuracy Assessment

Classification accuracy was evaluated using 210 independent ground truth points collected through field surveys and high-resolution imagery interpretation. A confusion matrix was generated to calculate accuracy metrics, including

- Overall accuracy
- Producer's and user's accuracy
- Kappa coefficient

The final classification achieved an overall accuracy of 89.3% with a Kappa coefficient of 0.86, indicating strong classification reliability.

2.8 | Disaster Data Collection and Analysis

Data on flood and landslide occurrences were compiled from woreda DRM office records covering the period 2013–2023 and validated through community recall during household surveys and focus group discussions.

To reduce spurious correlations, spatial analyses controlled for key confounding variables, including slope gradient, elevation, rainfall intensity, lithology, and road density.

Forest cover and disaster frequency relationships were analyzed using Pearson correlation and multiple regression models, with statistical significance evaluated at $p < 0.05$.

2.9 | Socioinstitutional Data Collection

Sociocultural and governance data were collected using the following:

- Household surveys ($n = 120$), selected through stratified random sampling;
- Key informant interviews (KIIs) ($n = 15$) with forestry experts, DRM officers, cooperative leaders, and elders;
- Focus group discussions (FGDs) conducted in Essera, Mareka, and Tocha woredas (8–12 participants per group).

Data collection instruments focused on perceptions of forest ecosystem services, disaster experiences, traditional forest management practices, and institutional coordination.

2.10 | Data Analysis

Quantitative ecological and spatial data were analyzed using *R* software, Microsoft Excel, and QGIS. Differences in biomass and microclimate variables among forest types were tested using one-way ANOVA, followed by Tukey's HSD post hoc tests.

Qualitative data from KIIs and FGDs were transcribed, coded, and analyzed thematically using NVivo software. Triangulation of ecological, spatial, and socioinstitutional data enhanced result validity and interpretation.

TABLE 1 | Aboveground biomass and carbon stock by forest type (mean ± 95% CI).

Forest type	Biomass (t ha^{-1})	Carbon stock (t C ha^{-1})
Natural moist forest	180.5 ± 18.7	84.84 ± 8.79
Plantation forest	140.3 ± 15.2	65.94 ± 7.14
Agroforestry system	98.6 ± 11.4	46.34 ± 5.36
Degraded forest	75.4 ± 9.6	35.44 ± 4.51

TABLE 2 | Microclimatic variables by forest type (mean ± SD).

Forest type	Air temp. (°C)	Soil temp. (°C)	Relative humidity (%)	Soil moisture (%)
Natural moist forest	18.4 ± 1.2	20.1 ± 1.5	88.7 ± 4.1	34.5 ± 3.8
Plantation forest	21.3 ± 1.4	23.6 ± 1.6	75.2 ± 5.3	27.6 ± 3.1
Agroforestry system	22.7 ± 1.5	24.9 ± 1.8	70.5 ± 4.9	25.3 ± 2.7
Degraded forest	25.6 ± 1.6	27.4 ± 1.9	61.1 ± 5.6	19.8 ± 2.9

Note: ANOVA results indicate significant differences among forest types ($p < 0.01$). Natural forests reduced air temperature by up to 7.2°C and increased soil moisture by 14.7% compared to degraded areas, supporting their role in climate buffering [10].

2.11 | Ethical Considerations

Ethical approval was obtained from the Institutional Review Board of Wolaita Sodo University. Informed consent was secured from all participants prior to data collection, and confidentiality was strictly maintained.

3 | Results and Discussion

3.1 | Forest Biomass and Carbon Stock Across Forest Types

Significant variation in AGB and carbon stock was observed among forest types in Dawro Zone (Table 1). Natural moist forests exhibited the highest mean biomass and carbon stock, while degraded forests showed the lowest values.

One-way ANOVA revealed statistically significant differences among forest types ($F = 18.72$, $p < 0.001$). Tukey's post hoc test confirmed that natural forests store significantly more carbon than all other land-use categories. These findings reflect the structural complexity and ecological integrity of native forests and are consistent with the studies from southwestern Ethiopia [20].

3.2 | Microclimate Regulation by Forest Ecosystems

Microclimate measurements differed significantly among forest types (Table 2). Natural forests provided strong buffering effects by lowering temperature and maintaining higher humidity and soil moisture.

3.3 | Forest Cover and Disaster Occurrence

A clear inverse relationship was observed between forest cover and disaster frequency (Table 3). Kebeles with higher forest cover experienced fewer flood and landslide events.

TABLE 3 | Forest cover and disaster frequency (2013–2023).

Site (kebele)	Forest cover (%)	Flood events	Landslide events
Oki	70	1	0
Tuta	45	2	1
Agara	30	3	2
Bato	15	5	4

Note: Correlation analysis showed significant negative relationships between forest cover and flood frequency ($r = -0.87$, $p < 0.01$) and landslide events ($r = -0.81$, $p < 0.01$). After controlling for slope, rainfall, lithology, and road density, forest cover remained a significant predictor of reduced disaster occurrence.

3.4 | Land Use/Land Cover Change in Dawro Zone (2000–2020)

Remote sensing analysis indicates substantial land cover change over the past 2 decades (Table 4).

The decline of natural forests alongside the expansion of agriculture and degraded land suggests increasing pressure on ecosystem services. Although plantation forests expanded, they cannot fully replace the multifunctional role of native forests.

TABLE 4 | Land use/land cover change in Dawro Zone (2000–2020).

Land use type	Area 2000 (ha)	Area 2020 (ha)	Change (%)
Natural forest	82,000	59,400	−27.6
Plantation forest	12,000	22,700	+89.2
Agricultural land	48,500	63,800	+31.5
Degraded/bare land	5800	13,600	+134.5

TABLE 5 | Community perception of forest functions (%).

Statement	Strongly agree	Agree	Neutral	Disagree
Forest reduces local temperature	62	28	6	4
Forest prevents floods and landslides	55	33	8	4
Forest cover is declining	70	21	6	3
Forest should be prioritized in DRR policy	66	25	7	2

Note: Over 90% of respondents recognized forests' roles in climate regulation and disaster mitigation, aligning with empirical results and highlighting opportunities for participatory forest management.

TABLE 6 | Institutional roles in forest-based DRR.

Institution	Key role	Implementation gap
Bureau of Agriculture	Tree planting, forest protection	Limited technical capacity
DRM Commission	Hazard mapping, early warning	Weak linkage with forestry
Local government	By-law enforcement	Poor coordination
NGOs	Awareness, restoration support	Short-term projects

Note: Fragmented institutional mandates constrain ecosystem-based disaster risk reduction (Eco-DRR) implementation, underscoring the need for integrated governance frameworks.

3.5 | Community Perception of Forest Ecosystem Services

Survey results show strong local awareness of forest ecosystem services (Table 5).

3.6 | Institutional Roles and Implementation Gaps

Institutional assessment reveals gaps between policy recognition and implementation (Table 6).

3.7 | Synthesis and Eco-DRR Implications

The combined evidence from biomass estimation, microclimate monitoring, disaster analysis, and community perceptions demonstrates that forest ecosystems in Dawro Zone function as natural infrastructure for climate regulation and DRR. Protecting remaining natural forests and restoring degraded areas—especially on steep slopes and riparian zones—could generate substantial cobenefits for carbon sequestration, hazard mitigation, and livelihood resilience.

4 | Conclusion

This study demonstrates that forest ecosystems in Dawro Zone play a substantial role in climate regulation and DRR. Natural moist forests store significantly higher AGB and carbon stocks than plantation, agroforestry, and degraded forests, confirming their importance for climate change mitigation. Microclimate measurements show that intact forests markedly reduce air and soil temperatures, enhance relative humidity, and maintain higher soil moisture, thereby buffering local climate extremes. Spatial and statistical analyses further reveal a strong inverse relationship between forest cover and the frequency of floods and landslides, even after accounting for key biophysical factors such as slope and rainfall. Despite these benefits, remote sensing analysis indicates a 27.6% decline in natural forest cover between 2000 and 2020, driven mainly by agricultural expansion and land degradation. Overall, the findings confirm that forests in Dawro Zone function as critical natural infrastructure, providing combined climate, ecological, and DRR services that are increasingly threatened by land-use change.

5 | Recommendations

Based on the study findings, the following actions are recommended:

- ❖ Prioritize protection of remaining natural forests, as they provide the highest carbon storage and strongest microclimate and disaster-mitigation benefits.
- ❖ Target forest restoration in degraded and high-risk areas, particularly steep slopes, riparian zones, and flood-prone landscapes, to enhance DRR and climate resilience.
- ❖ Integrate forest-based solutions into disaster risk management planning, recognizing forests as cost-effective, ecosystem-based infrastructure for flood and landslide mitigation.
- ❖ Strengthen coordination between forestry and disaster management institutions to improve implementation of Eco-DRR strategies.
- ❖ Promote community-based forest management, building on high local awareness of forest ecosystem services to support sustainable conservation and restoration efforts.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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