Seasonal herbaceous biomass dynamics in disturbed and undisturbed riparian zones of the Dikhu River, Nagaland, India

Watijungla Jamir[1], iD Akumlong Pongen[2], iD Wati Temjen[3], iD Pukhrambam Rajesh Singh[4], iD and Maibam Romeo Singh*[1] iD

[1]Department of Botany, Nagaland University, Lumami-798627, Nagaland, India
[2]Department of Chemistry, Phek Government College, Phek Town -797108, Nagaland, India
[3]Department of Botany, Fazl Ali College, Mokokchung-798601 Nagaland, India
[4]Department of Zoology, Nagaland University, Lumami-798627, Nagaland, India

ABSTRACT

Riparian ecosystems represent dynamic interfaces between terrestrial and aquatic environments and play an important role in maintaining ecological stability and water quality. The present study investigated herbaceous species composition and biomass dynamics along disturbed and undisturbed stretches of the Dikhu River, Nagaland. Field sampling was conducted for three seasons (November, Winter 2022 to July, Monsoon 2023) using a quadrat-based direct harvest method across upper, middle and lower riparian zones. A total of 33 herbaceous species belonging to 22 families were recorded. Above-ground biomass consistently exceeded below-ground biomass across all months and zones. Seasonal variation was evident, with maximum biomass recorded in pre-monsoon, followed by monsoon, while winter exhibited comparatively lower values. The undisturbed site generally supported greater biomass accumulation and presence of moisture-associated taxa, whereas the disturbed stretch was dominated by opportunistic and disturbance-tolerant species. Members of Asteraceae contributed substantially to total biomass across sites. The findings indicate that herbaceous biomass distribution in the Dikhu riparian system is strongly influenced by seasonal growth dynamics and disturbance regimes. Protection of undisturbed riparian stretches and reduction of anthropogenic pressure are essential for maintaining vegetation structure and ecological integrity of the riverine ecosystem.

Introduction

Riparian zones are ecotonal landscapes situated at the interface of terrestrial and aquatic ecosystems. The term "riparian," derived from the Latin *riparius* meaning "river bank," refers to land and biota occurring along rivers, streams, lakes, and wetlands [1, 2]. These zones function as dynamic transition areas where hydrological, geomorphological, and biological processes interact across spatial and temporal scales. Because of their position at the land–water boundary, riparian ecosystems exert strong influences on stream ecology, wildlife habitat, nutrient cycling, and sediment dynamics [3]. Riparian vegetation is structurally and compositionally diverse, typically comprising overstory trees, understory shrubs, herbaceous layers, and aquatic macrophytes [4]. Vegetation patterns are strongly influenced by hydrology, soil characteristics, climate, geomorphology, and disturbance regimes [5]. Owing to this environmental heterogeneity, riparian ecosystems are often characterized by high species diversity and productivity but are also among the most vulnerable to anthropogenic disturbance [2].

Biomass represents the standing stock of living organic matter per unit area, while productivity reflects the rate of biomass accumulation over time. Net primary productivity (NPP) is defined as gross photosynthetic production minus respiratory losses and determines biomass accumulation in terrestrial ecosystems [6]. In forest ecosystems, biomass is commonly partitioned into above- and below-ground components. Above-ground net primary production (ANPP) specifically represents the annual increment in living biomass per unit area. Although biomass and productivity are related, they are not always directly proportional, as both are influenced by multiple interacting biotic and abiotic factors. Climatic variables such as rainfall, temperature, and solar radiation strongly regulate biomass accumulation and productivity, both directly and indirectly through their effects on forest structure and species composition. Edaphic factors, including soil nutrient availability and moisture, further modulate biomass patterns, though reported relationships range from positive to negative depending on site conditions and spatial scale [7]. While numerous studies have examined the structure and functioning of woody riparian vegetation [8-10], comparatively less

attention has been given to herbaceous components. Herbaceous species typically exhibit faster turnover rates and greater responsiveness to disturbance than long-lived woody species. Consequently, they may serve as sensitive indicators of environmental change and anthropogenic impacts within riparian systems. In northeastern India, riparian ecosystems remain poorly documented despite increasing anthropogenic pressures [11, 12]. The Dikhu River in Nagaland represents an important fluvial system where sections of riparian habitat experience varying degrees of disturbance. However, quantitative assessments of herbaceous biomass patterns under disturbed and undisturbed conditions are limited. Therefore, the present study aimed to (i) compare herbaceous species composition between disturbed and undisturbed riparian zones along the Dikhu River, and (ii) evaluate seasonal and spatial variation in above- and below-ground biomass across zonal gradients. The findings provide baseline ecological information that may support future riparian management and conservation efforts in the region.

Materials and Methods
2.1 Study Area
The study was conducted along the riparian zone of the Dikhu River at Longsa Village, Mokokchung district, Nagaland, India. The site is located at 26.252902°N and 94.530050°E, at an elevation of 692.82 m above sea level. The Dikhu River is a major tributary of the Brahmaputra River, flowing through Mokokchung and Longleng districts. Two contrasting sites were selected based on disturbance regimes: Disturbed site – characterized by agricultural activity and livestock grazing and an Undisturbed site – downstream forested stretch with minimal anthropogenic interference. Each site covered approximately 350 m along the riverbank and was subdivided into three zones (upper, middle, and lower) to capture spatial heterogeneity within the riparian gradient.

2.2 Sampling Design and Vegetation Analysis
Field sampling was conducted seasonally (November, postmonsoon 2022, March, premonsoon, 2023 and July, Monsoon 2023). A quadrat-based direct harvest method was employed to estimate herbaceous biomass. At each site, 60 quadrats (1 m × 1 m) were randomly placed, with 10 quadrats sampled in each of the three zones (upper, middle, lower) at both disturbed and undisturbed riparian sites. All herbaceous species within each quadrat were recorded and identified using standard floristic literatures [12].

2.3 Biomass Estimation
2.3.1 Harvesting
All herbaceous vegetation within each quadrat (1 m^2) was carefully uprooted. Collected plant material, including loose litter, was placed in labeled plastic bags for processing.

2.3.2 Sorting
Samples were sorted to separate living biomass from necrotic material. Plant material was further segregated into: above-ground components (stems, leaves, flowers, seeds) and below-ground components (roots and rhizomes)

2.3.3 Drying and Weighing
Samples were washed to remove adhering soil and oven-dried at constant temperature until constant weight was achieved. Dry weights were recorded using a precision balance. Total biomass in term of g/m^2/dry weight [13] was calculated as:

$$\frac{Total\ Dry\ Weight\ of\ sample\ (g)}{Area\ of\ Quadrat\ (m^2)}$$

Results and Discussion
Species composition and richness
A total of 33 herbaceous species belonging to 22 families were recorded from the riparian belt of the Dikhu River across the disturbed and undisturbed sites (Table 1). The assemblage was dominated by members of Asteraceae, which contributed several frequent and high-biomass taxa including *Ageratum conyzoides*, *Pseudognaphalium affine*, *Acmella uliginosa*, *Bidens pilosa*, and *Eupatorium adenophorum*. The distribution of species across the three zones (upper, middle, lower) and across months showed clear turnover, reflecting the combined influence of microhabitat conditions along the riparian gradient and disturbance intensity. Zone-wise and seasonal wise species occurrence and biomass are presented in Tables 2–7.

Biomass allocation pattern: above-ground exceeds below-ground
Across all zones, above-ground biomass (AGB) was consistently higher than below-ground biomass (BGB) (Tables 2–7). This AGB>BGB pattern is ecologically plausible for riparian herbaceous communities growing on shallow, heterogeneous substrates where root penetration and storage are constrained. In the present study, field observations indicated a relatively shallow soil layer overlying rocks and boulders in several quadrats, which can reduce rooting depth and total root mass. In addition, acidic soils and nutrient limitation can suppress root proliferation and below-ground investment, resulting in proportionally lower BGB [14, 15]. Therefore, the consistently lower BGB across zones likely reflects substrate and edaphic constraints rather than sampling artefacts.

Seasonal variation in biomass
Clear seasonal differences in standing biomass were observed. When comparing the three sampling seasons, both AGB and BGB were highest in pre-monsoon, followed by monsoon, while winter (2022) recorded the lowest values (Tables 2–7). This pattern suggests that herbaceous standing crop along the Dikhu riparian belt increases from the post-monsoon period into late winter/early spring, reaching a peak around pre-monsoon. Seasonal phenology and climatic conditions can strongly regulate herb biomass accumulation; during late winter and early spring, many herbaceous taxa exhibit rapid vegetative growth and canopy expansion, which increases above-ground mass [16, 17]. The relatively lower biomass in winter likely reflects post-monsoon senescence of short-lived species and reduced growth rates during the onset of the cooler season.

Spatial variation: effects of disturbance and zonation
Biomass and species composition differed between the disturbed (farming and grazing influence) and undisturbed (downstream forested) riparian stretches. The disturbed site supported a strong presence of opportunistic, disturbance-tolerant herbs (e.g., *Bidens pilosa*, *Galinsoga parviflora*, *Amaranthus spinosus*), consistent with open habitats and repeated biomass removal through grazing and trampling. Such disturbance regimes can favour fast-growing, short-lived species capable of rapid recolonization and high above-ground production. In contrast, the undisturbed site included moisture-associated and forest-edge taxa such as *Equisetum* sp., *Carex* sp. and *Dryopteris* sp. which were absent or less frequent in several disturbed-site zones, indicating that the downstream forested riparian segment offers more stable microclimatic and edaphic

conditions. Within each site, the division into upper, middle, and lower zones highlighted small-scale heterogeneity. Lower zones generally represent closer proximity to the active channel and therefore may experience higher soil moisture and periodic inundation, while upper zones are typically drier and more influenced by adjacent land use. The observed zonal differences in species presence and biomass therefore likely reflect gradients in moisture availability, substrate stability, and anthropogenic pressure along the riverbank [18].

Species dominance and contribution to biomass

Among all recorded species, *Ageratum conyzoides* consistently contributed the highest biomass across months and across both sites (Tables 2–7). The repeated dominance of *A. conyzoides* may be attributed to its ecological strategy as a highly competitive, disturbance-adapted herb with rapid growth, high reproductive output, and strong tolerance to variable soil and moisture conditions. Similar studies have reported that locally favourable environmental conditions and adaptive plasticity can enable particular herbaceous dominants to attain higher biomass and exert competitive control over community structure [19, 20]. Along with *A. conyzoides*, several Asteraceae taxa (*Acmella uliginosa*, *Pseudognaphalium affine*, *Eupatorium adenophorum*) also showed relatively high biomass in multiple zones, reinforcing the pattern that composites are key biomass contributors in these riparian habitats.

Interpretation of patterns and ecological implications

Taken together, the results indicate that herbaceous biomass in the Dikhu riparian system is shaped by a strong seasonal signal (pre-monsoon peak), consistent allocation toward above-ground structures, and spatial heterogeneity driven by disturbance regime and zonation. The disturbed area, influenced by cultivation and grazing, appears to favour ruderal, high-turnover herbs capable of maintaining high AGB despite repeated disturbance. Conversely, the undisturbed forested stretch supports a different set of taxa including moisture-associated and forest-edge species, suggesting that reduced human interference allows greater persistence of habitat-specific herbs. From a management perspective, these findings imply that increasing anthropogenic pressure along riparian

margins can lead to compositional shifts toward a few dominant, disturbance-tolerant species, potentially reducing functional diversity even if total above-ground biomass remains locally high. Protecting less-disturbed riparian stretches, particularly in lower zones closer to the channel, may therefore help conserve habitat heterogeneity and maintain riparian ecological functions such as bank stabilization, nutrient retention, and support for diverse terrestrial and aquatic biota.

Table 1: List of herbaceous species identified along the riparian zone

Species name	Family
Acmella paniculata (Wall. ex DC.) R.K.Jansen	Asteraceae
Acmella uliginosa (Swartz) Cassini	Asteraceae
Ageratum conyzoides (L.)	Asteraceae
Amaranthus spinosus (L.)	Amaranthaceae
Artemisia sp.	Asteraceae
Bidens pilosa L.	Asteraceae
Cardamine impateins L.	Brassicaceae
Carex sp.	Cyperaceae
Crassocephalum crepedioides (Benth.) S. Moore.	Asteraceae
Cirsium arvense L.	Asteraceae
Cuphea cathagenesis (Jacq.) J.F. Macbr.	Lythreceae
Cyperus esculentus L.	Cyperaceae
Erigeron canadensis L.	Asteraceae
Equisetum sp.	Equisetaceae
Euphorbia hirta L.	Euphorbiaceae
Eupatorium adenophorum (Spreng.) R.M.King & H.Rob	Asteraceae
Galinsoga parviflora Cav.	Asteraceae
Gomphostemma nutans Hook.f.	Lamiaceae
Nelsonia canescens (Lam.) Spreng.	Acanthaceae
Oxyspora sp.	Melastomataceae
Perilla frutescens (L.) Britton	Lamiaceae
Persicaria chinensis (L.) H.Gross	Polygonaceae
Persicaria hydropiper L.	Polygonaceae
Plantago asiatica L.	Plantaginaceae
Pseudognaphalium affine (D.Don) Anderb	Asteraceae
Impatiens latiflora L.	Balsaminaceae
Salomonia cantoniensis Lour.	Polygonaceae
Solanum torvum Sw.	Solanaceae
Stachys arvensis (L.) L.	Labiatae
Stachytarpheta indica (L.) Vahl	Verbenaceae
Torenia violacea (Azaola) Pennell	Linderniaceae
Urena lobata L.	Malvaceae
Dryopteris sp.	Dryopteridaceae

Table 2: Biomass (g/m²/dry weight) of riparian vegetation along Disturbed area for the month of winter

Family	Species	Biomass at Lower zone		Biomass at Middle zone		Biomass at Upper zone	
		Above Ground	Below Ground	Above Ground	Below Ground	Above Ground	Below Ground
Asteraceae	*Ageratum conyziodes* (L.)	11.76	6.38	21.79	4.21	24.17	5.88
Amaranthaceae	*Amaranthus spinosus* (L.)	10.6	5.2	-	-	-	-
Asteraceae	*Acmella uliginosa* (Swartz) Cassini	19.8	4.3	10.68	3.68	18.17	5.65
Asteraceae	*Bidens pilosa* L.	24.66	6.46	-	-	28.62	7.13
Polygonaceae	*Persicaria hydropiper* L.	20.17	9.5	28.24	13.3	-	-
Plantaginaceae	*Plantago asiatica* L.	7.05	1.07	5.75	1.8	4.67	1.41
Acanthaceae	*Nelsonia canescens* (Lam.) Spreng	8.26	2.06	6.06	2.13	-	-
Asteraceae	*Crassocephalum crepedioides* (Benth.) S. Moore.	-	-	34.86	12.6	29.97	7.95
Asteraceae	*Galinsoga parviflora* Cav.	-	-	12.58	6.4	16.45	6.01
Melastomataceae	*Oxyspora* sp.	-	-	21.57	7.2	10.17	5.65
Malvaceae	*Urena lobata* L.	-	-	13.91g	8.44	4.16g	2.86
Cyperaceae	*Cyperus esculentus* L.	-	-	6.3	4.3	5.9	1.8
Euphorbiaceae	*Euphorbia hirta* L.	-	-	7.7	2.74	15.4	3.56
Lamiaceae	*Perilla frutescens* (L.) Britton	-	-	-	-	133.2	4.2

Table 3: Biomass (g/m²/dry weight) of riparian vegetation along Undisturbed area for the month of winter

Family	Species	Biomass at Lower zone		Biomass at Middle zone		Biomass at Upper zone	
		Above Ground	Below Ground	Above Ground	Below Ground	Above Ground	Below Ground
Asteraceae	*Ageratum conyziodes* (L.)	33.04	5.75	26.57	6.35	10.35	5.35
Equisetaceae	*Equisetum* sp.	5.9	1.86	-	-	-	-
Brassicaceae	*Cardamine impateins* L.	12.3	2.54	7.7	3.45	8.16	1.9
Polygonaceae	*Persicaria hydropiper* L.	20.75	6.28	30.86	9.36	12.13	1.36
Polygonaceae	*Persicaria chinensis* (L.) H.Gross	9.07	2.15	11.1	4.	-	-
Solanaceae	*Solanum torvum* Sw.	16.35	7.91	-	-	11.3	3.35
Balsaminaceae	*Impatiens latiflora* L.	7.07	3.91	8.06	1.9	-	-
Polygonaceae	*Salomonia cantoniensis* Lour.	-	-	7.56	2.23	-	-
Lamiaceae	*Gomphostemma nutans* Hook.f.	-	-	9.17	1.47	8.84	1.82
Asteraceae	*Eupatorium adenophorum* (Spreng.) R.M.King & H.Rob	-	-	18.32	4.71	19.73	5.33
Dryopteridaceae	*Dryopteris* sp.	-	-	8.6	1.86	-	-
Asteraceae	*Pseudognaphalium affine* (D.Don) Anderb	-	-	14.3	6.05	14.6	3.32

Table 4: Biomass (g/m²/dry weight) of riparian vegetation along Disturbed area for the month of pre-monsoon

Family	Species	Biomass at Lower zone		Biomass at Middle zone		Biomass at Upper zone	
		Above Ground	Below Ground	Above Ground	Below Ground	Above Ground	Below Ground
Asteraceae	*Ageratum conyziodes* (L.)	22.58	6.97	30.47	14.42	22.58	4.11
Asteraceae	*Crassocephalum crepedioides* (Benth.) S. Moore.	15.43	8.22	-	-	32.36	8.51
Asteraceae	*Bidens pilosa* L.	23.31	9.67	-	-	16.19	8.51
Linderniaceae	*Torenia violacea* (Azaola) Pennell	9.13	1.7	-	-	9.45	1.35
Acanthaceae	*Nelsonia canescens* (Lam.) Spreng.	8.55	2.0	7.5	3.6	-	-
Asteraceae	*Pseudognaphalium affine* (D.Don) Anderb	23.6	5.48	16.18	4.65	19.64	5.05
Asteraceae	*Cirsium arvense* L.	7.3	3.72	-	-	7.15	1.7
Asteraceae	*Eupatorium adenophorum* (Spreng.) R.M.King & H.Rob	28.69	7.47	16.8	8.4	22.6	3.96
Polygonaceae	*Persicaria hydropiper* L.	21.63	10.57	20.11	8.73	-	-
Lythreceae	*Cuphea cathagenesis* (Jacq.) J.F. Macbr	15.46	9.58	12.6	6.97	16.3	6.32
Asteraceae	*Acmella uliginosa* (Swartz) Cassini	30.68	7.74	15.7	4.71	7.95	1.62
Labiatae	*Stachys arvensis* (L.) L.	13.14	6.43	-	-	30.32	4.18
Asteraceae	*Galinsoga parviflora* Cav.	-	-	10.93	6.43	20.21	5.17
Plantaginaceae	*Plantago asiatica* L.	-	-	7.2	2.89	13.33	3.52
Asteraceae	*Artemisia* sp.	-	-	39.53	11.2	18.7	6.65

Table 5: Biomass (g/m²/dry weight) of riparian vegetation along Undisturbed area for the month of pre-monsoon

Family	Species	Biomass at Lower zone		Biomass at Middle zone		Biomass at Upper zone	
		Above Ground	Below Ground	Above Ground	Below Ground	Above Ground	Below Ground
Asteraceae	*Ageratum conyziodes* (L.)	38.9	11.47	20.36	5.37	25.01	5.6
Equisetaceae	*Equisetum* sp.	17.76	5.57	10.32	5.2	14.73	7.63
Balsaminaceae	*Impatiens latiflora* L.	26.48	8.72	6.05	1.75	31.9	8.66
Verbenaceae	*Stachytarpheta indica* (L.) Vahl	28.78	10.7	-	-	17.61	3.48
Asteraceae	*Pseudognaphalium affine* (D.Don) Anderb	11.15	2.6	21.93	4.3	24.67	4.83
Asteraceae	*Cirsium arvense* L.	21.1	8.11	17.06	5.9	-	-
Dryopteridaceae	*Dryopteris* sp.	5.96	2.33	-	-	-	-
Asteraceae	*Acmella uliginosa* (Swartz) Cassini	6.23	1.9	13.47	6.82	21.63	4.56
Brassicaceae	*Cardamine impateins* L.	15.88	5.28	18.16	9.31	-	-
Cyperaceae	*Carex* sp.	13.1	7.91	-	-	33.11	6.61
Lythreceae	*Cuphea cathagenesis* (Jacq.) J.F. Macbr.	23.8	6.38	18.56	3.58	21.82	6.52
Solanaceae	*Solanum torvum* Sw.	-	-	6.95	1.62	12.73	7.16
Polygonaceae	*Salomonia cantoniensis* Lour.	-	-	14.41	5.23	17.12	6.87

Table 6: Biomass (g/m²/dry weight) of riparian vegetation along Disturbed area for the month of monsoon

Family	Species	Biomass at Lower zone		Biomass at Middle zone		Biomass at Upper zone	
		Above Ground	Below Ground	Above Ground	Below Ground	Above Ground	Below Ground
Asteraceae	*Ageratum conyziodes* (L.)	14.73	5.16	10.88	4.62	23.11	5.41
Asteraceae	*Crassocephalum crepedioides* (Benth.) S. Moore.	17.92	4.68	11.18	4.27	24.12	5.9
Asteraceae	*Artemisia* sp.	18.88	6.48	-	-	6.32	2.07
Plantaginaceae	*Plantago asiatica* L.	4.68	2.11	19.46	9.13	6.65	4.2
Asteraceae	*Bidens pilosa* L.	15.31	5.32	13.6	2.82	19.44	4.58
Labiatae	*Stachys arvensis* (L.) L.	16.12	5.58	11.97	5.35	20.26	5.6
Malvaceae	*Urena lobata* L.	14.86	2.76	23.52	7.31	7.7	4.5
Asteraceae	*Pseudognaphalium affine* (D.Don) Anderb	17.45	8.8	-	-	24.83	3.73
Asteraceae	*Acmella uliginosa* (Swartz) Cassini	12.25	5.78	15.63	4.39	23.63	3.65
Asteraceae	*Acmella paniculata* (Wall. ex DC.) R.K.Jansen	5.62	1.57	-	-	-	-
Asteraceae	*Eupatorium adenophorum* (Spreng.) R.M.King & H.Rob	12.65	6.46	17.22	5.17	20.48	4.49
Lythreceae	*Cuphea cathagenesis* (Jacq.) J.F. Macbr.	10.76	5.21	-	-	27.06	11.73
Asteraceae	*Galinsoga parviflora* Cav	-	-	22.2	7.27	21.18	7.17
Polygonaceae	*Persicaria hydropiper* L.	-	-	14.03	6.03	-	-

Table 7: Biomass (g/m²/dry weight) of riparian vegetation along Undisturbed area for the month of monsoon

Family	Species	Biomass at Lower zone		Biomass at Middle zone		Biomass at Upper zone	
		Above Ground	Below Ground	Above Ground	Below Ground	Above Ground	Below Ground
Asteraceae	*Ageratum conyziodes* (L.)	24.68	8.87	16.32	5.72	16.82	4.88
Equisetaceae	*Equisetum* sp.	13.73	3.41	32.22	6.45	8.65	2.77
Brassicaceae	*Cardamine impateins* L.	23.8	7.27	8.72	3.98	-	-
Polygonaceae	*Persicaria hydropiper* L.	24.1	3.9	27.52	4.9	22.9	8.3
Balsaminaceae	*Impatiens latiflora* L	24.23	6.11	17.03	8.03	-	-
Verbenaceae	*Stachytarpheta indica* (L.) Vahl	32.55	9.82	23.31	5.56	24.85	5.47
Dryopteridaceae	*Dryopteris* sp.	9.63	2.06	6.45	3.37	-	-
Solanaceae	*Solanum torvum* Sw.	8.3	2.4	-	-	13.2	7.05
Melastomataceae	*Oxyspora* sp.	11.83	5.53	19.4	4.78	10.62	4.2
Cyperaceae	*Carex* sp.	-	-	21.16	7.18	27.1	5.12
Lythreceae	*Cuphea cathagenesis* (Jacq.) J.F. Macbr.	-	-	21.7	5.06	9.06	4.36
Asteraceae	*Pseudognaphalium affine* (D.Don) Anderb	-	-	15.75	5.64	23.15	5.92
Polygonaceae	*Salomonia cantoniensis* Lour.	-	-	13.25	7.87	-	-

Conclusion

The present study recorded 33 herbaceous species belonging to 22 families along the riparian zone of the Dikhu River, highlighting substantial floristic diversity across disturbed and undisturbed stretches. Asteraceae was the most dominant family in terms of representation and biomass contribution. Above-ground biomass consistently exceeded below-ground biomass across all months and zones, indicating limited root development likely influenced by shallow soils and rocky substrata. Clear seasonal variation was observed, with biomass peaking in pre-monsoon, followed by monsoon, while winter exhibited comparatively lower values. These differences reflect seasonal growth dynamics of riparian herbaceous vegetation. The undisturbed site generally supported greater biomass accumulation compared to the disturbed stretch, suggesting that reduced human interference and absence of grazing favour higher vegetative development. In contrast, the disturbed site was characterized by dominance of opportunistic and disturbance-tolerant species. Overall, the findings demonstrate that herbaceous biomass distribution along the Dikhu riparian zone is strongly regulated by seasonal factors, zonal heterogeneity, and disturbance regimes. Conservation and improved management of riparian stretches, particularly minimizing anthropogenic pressure, are essential for maintaining vegetation structure and sustaining riverine ecosystem stability.

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