Forest is the most important natural resource in the world fulfilling the diverse requirements of human population. Biodiversity of the forest ecosystems of the world is under threat due to forest fragmentation. Forest fragmentation refers to any process that leads to conversion of continuous forests into patches of forest fragments separated by non-forested land. Indiscriminate use of forest resources and over-exploitation of forest produces have caused serious damage to natural forest ecosystems and rich biodiversity of the Himalayan region. Loss of diversity and structural damage of forest communities limits plant recruitment and decreases the ecosystem productivity, affecting the overall ecosystem functioning (Symstad & Tilman 2001).

The forest ecosystems of Khangchendzonga Biosphere Reserve (KBR) (27°06′-28°05′ N, 88°02′-88°47′ E) in the Eastern Himalayan state of Sikkim in north-eastern India is under pressure from the growing needs of human population and other anthropogenic/biotic pressures such as cattle grazing, landslide, forest fire etc., posing serious threats to the several taxonomically and ethnomedicinally important plant species. The present study was conducted in three forest types viz. Lower montane, Montane and Upper montane forests of KBR to understand the effect of forest fragmentation on plant diversity and regeneration. The main objectives of the present work were to: (1) To prepare an inventory of plant species including lianas and epiphytes, (2) To study the causes and pattern of forest fragmentation in KBR and (3) To study regeneration ecology of a few taxonomically and ethnomedicinally important tree and liana species.

The findings of the study are summarized below:

- The number of plant species in different lifeforms was highest in the Lower montane, than in the Montane and Upper montane forests. Seventy eight tree species with 47 genera and 30 families were recorded from the three forest types. Thirty eight shrub species belonging to 35 genera and 17 families were recorded. On the forest floor,
133 herb species belonging to 97 genera and 49 families were documented. Ninety two epiphyte species belonging to 57 genera and 31 families were recorded. Forty three liana species belonging to 37 genera and 28 families were recorded from the three forest types.

- $\alpha$- diversity values and dominance indices for all the lifeforms decreased with increasing elevation except the dominance index for epiphytes, which remained same in the Montane and the Lower montane forests. However, it was the least in the Upper montane forest.

- $\beta$-diversity values between the Lower montane and Upper montane forests for all the lifeforms were highest and ranged between 0.71 to 0.98. As expected, adjacent forests had lower $\beta$-diversity values than the fragments. Amongst the lianas, $\beta$-diversity value was lower compare to other lifeforms studied.

- Forest types differed significantly in plant species composition (tree, shrubs, herbs, epiphytes and lianas; Clark’s $R$ statistic = 0.95, 0.63, 0.95, 0.47, 0.64 respectively and $P < 0.001$ for all).

- The density of tree decreased with increasing elevation ($F = 22.50, P < 0.001$). Tree density was highest in the Lower montane (463 stems ha$^{-1}$) forests followed by the Montane (239 stems ha$^{-1}$), and the Upper montane forests (256 stems ha$^{-1}$). Overall density of the shrubs differed significantly among the forest types ($F = 11.82, P < 0.001$). It was highest in Lower montane forest (319 stems ha$^{-1}$) and lowest in the Montane forest (101 stems ha$^{-1}$) and again it increased to 234 stems ha$^{-1}$ in the Upper montane forest. On the other hand, density of herbaceous species did not differ significantly across the forest types ($F = 0.90, P = 0.44$). Highest density was in the Montane forests (711500 individual ha$^{-1}$), followed by the Upper montane and Lower montane forests (625000 individuals ha$^{-1}$ & 609500 individuals ha$^{-1}$ respectively). The density of epiphytes decreased significantly along the elevation ($F = 8.53, P =$
0.001). It was highest in the Lower montane forests (5200 individuals 20 tree\(^{-1}\)), followed by the Montane and the Upper montane forests (4830 & 2390 individuals 20 tree\(^{-1}\) respectively). Liana density also decreased with increasing elevation \((F = 70.18, P < 0.001)\). It had 83 stems ha\(^{-1}\) in the Lower montane, 73 stems ha\(^{-1}\) in the Montane and 38 stems ha\(^{-1}\) in the Upper montane forest.

- With an increase in elevation, the trees, shrubs, herbs, epiphytes, and liana species-abundance curves exhibited higher dominance. The common tree species were *Alnus nepalensis*, *Castanopsis hystrix*, *Elaeocarpus lanceaefolius*, *Eurya acuminata* and *Rhus javanica* in the Lower montane forests. *Lithocarpus pachyphylla*, *Quercus lamellosa*, *Q. lineata* and *Rhododendron arboreum* in the Montane forests. *Abies densa* and *Rhododendron* spp., were common in the Upper montane forests. Amongst the shrubs, dominant species in the Lower montane forests were *Elsholtzia flava*, *Melastoma normale*, *Oxyspora paniculata*, *Rubus ellipticus*, *Rubus mollucanus*, and *Thysaenolaena maxima*. *Arundinaria maling*, *Deutzia compacta* and *Rosa sericea* were dominant in the Montane forests while, *Berberis* spp., *Rhododendron anthropogon*, *R. lepidotum* were dominant in the Upper montane forests. In the herbaceous flora, *Bidens pilosa*, *B. biternata*, *Carex filicina*, and *Elsholtzia blanda* were dominant in the Lower montane forests. *Fragaria nubicola*, *Persicaria runcinata*, *Phlomis bracteosa* were dominant in the Montane forests, while *Anaphalis triplinervis*, *Juncus* spp., and *Poa alpina* were dominant in the Upper montane forests. Amongst the epiphytes, Pteridophytic species were dominant in all the forest stands. The three dominant and codominant epiphyte species in the Lower montane forests were *Hoya linearis*, *Lepisorus nudus* and *Vittaria elongata*. In the Montane forests the three dominants species were, *V. elongata*, *L. nudus* and *Pleione humilis*. In the Upper montane forests dominant species were *Cystopteris sudetica*, *Onychium* spp., and *P. humilis*. Amongst the lianas, *Cissus repens*, *Clematis acuminata*, *Hydrangea*
*anomala* and *Parthenocissus himalayana* together were dominant in the Lower montane forests, while *Actinidia callosa*, *Holboellia latifolia*, *Rubus paniculatus*, and *Schisandra grandiflora* were dominant in the Montane forests. *A. callosa*, *Clematis montana*, *H. latifolia*, *Schisandra neglecta*, and *S. grandiflora* were dominant in the Upper montane forests.

- Epiphytes with Caespitose life form were highest. According to taxonomic classification, pteridophytic community was the highest, followed by herbaceous, shrubby and climbing epiphytes. Shrubby and climbing epiphytes contributed substantially to total epiphytes composition.

- Tall trees with larger girth supported greater number of epiphytes in all the forests.

- Tree basal area was highest in the Lower montane forest (92.57 m² ha⁻¹) compared to the Montane and the Upper montane forests (49.96 and 58.04 m² ha⁻¹, respectively). The basal area of lianas also followed a similar trend, i.e. 3.54, 2.25 and 0.13 m² ha⁻¹ in the Lower montane, Montane and Upper montane forests, respectively.

- Microenvironmental variables viz. air temperature, soil temperature, soil moisture content, Phosphorus (P) and Nitrogen (N) varied significantly (ANOVA *P* < 0.01) among the three forest types. Air temperature, soil temperature, soil moisture content, soil Carbon (C) and N varied significantly (ANOVA *P* < 0.05) among the seasons.

- Although CCA explained overall poor species-environment relationship for all the vegetation components i.e. tree, shrub, herbs, epiphytes and liana across the forest types (explaining only about 20% of variabilities), the relationship with microenvironmental factors was significant (Monte Carlo test; *P* < 0.009).

- Soil N, pH, P and proxy variable ‘elevation’ were important determinants of tree species distribution across the forest types. On the other hand, soil N, C, pH, P and K were important determinants of shrub and herb species distribution across the forest types. While air temperature and the proxy variable ‘elevation’ were important
determinants of epiphyte species distribution across the forests. Liana species distribution across the forest types was determined by light, soil pH, N, P and the proxy variable ‘elevation’.

- Forward stepwise multiple regression analysis revealed that, soil N was significant in influencing the overall distribution of tree and shrub species along the forest types ($P = 0.000$). While, soil P alone was significant in influencing herb species distribution along the three forests ($P = 0.031$). Elevation ($P = 0.010$) alone, soil P and light ($P = 0.000$) were significant in influencing the overall distribution of epiphyte and liana species respectively across the forest types. Soil pH and air temperature in the Lower montane, and C in the Montane and Upper montane forests were important in influencing tree density. In case of shrubs light and soil C in the Lower montane, and soil C alone in the Montane and Upper montane forests were important. For the herbs, soil pH and elevations in the Lower montane, and soil N, P concentrations in the Montane and soil P alone in the Upper montane forests were important. Light in the Lower montane, elevation in the Montane and RH in the Upper montane forests were important in influencing epiphytes diversity. Light in the Lower montane, soil P concentration in the Montane, and both light and soil P in the Upper montane forests were important determinants of liana abundance.

- Extent of forest fragmentation in KBR was studied by analyzing the imageries pertaining to the three time intervals, i.e. 1999, 2002 and 2008. The total number as well as area under fragments represented a declining trend during the period, 1999 to 2008. Considerable changes were found in the distribution, number and size of forest fragments during the decade.

- The number of fragments in different size classes decreased sharply from 875 in 1999 to 533 during 2002 and again it increased to 615 during 2008. During the entire study
period, the average annual fragmentation rate was 0.7 ha year\(^{-1}\), equivalent to 0.007%.

- Mean fragment size decreased from 4.4 ha in 1999 to 3.9 ha in 2008. This decline in mean fragment size was associated with decrease in fragment density and a substantial reduction in the size of the largest forest fragments during the study period.

- Important causes of forests fragmentation in KBR were agriculture, grazing, NTFPs cultivation/extraction, timber/poles, trekking routes, settlement, tourism, road, wind-throw, landslide, snow avalanche, and wild fire. The anthropogenic disturbances from agriculture, NTFPs cultivation/extraction, and agriculture decreased sharply in 2008.

- Incision was the dominant process of fragmentation as revealed from the analysis of fragmentation process in 25 identified fragments.

- The species diversity indices of 25 forest fragments were lower than those of adjacent continuous forests.

- The \(\alpha\)-diversity for trees was significantly higher in the Montane forest fragments than in the other two forests.

- The \(\beta\)-diversity was high between Upper and Lower montane forest fragments (0.91), and Lower montane and Montane (0.81) forests. The Montane and Upper montane forest fragments had the lowest \(\beta\)-diversity value of 0.62. Within Montane forest, \(\beta\)-diversity between the largest fragment (72.2 ha) and smallest fragment (0.1 ha) was 0.50 and in the Upper montane forest \(\beta\)-diversity between the largest fragment (72.2 ha) and smallest one (1.02 ha) was 0.80.

- Air and soil temperature, light intensity decreased with increasing distance towards the forest interior, while relative humidity showed an increasing tendency.

- TWINSPAN analysis classified 71 tree species from 25 fragments into eight specific tree communities (C1-C8).
• TWINSPAN ordination of 25 forest fragments clearly showed the separation of fragments according to forest types.

• Tree species such as *Castanopsis hystrix*, *Alnus nepalensis*, *Buddleia colvilei*, *Ficus semicordata*, *Eurya acuminata* were found in the medium size fragments in the Lower montane forests. *Rhododendron hodgsonii*, *R. thomsonii*, was mostly found in smaller size fragments in the Upper montane forests. Larger fragments in Upper montane forests contained all the species from smaller and medium size fragments.

• The distribution of the tree species in the ordination space was performed using DECORANA according to tree community types and their area of occurrence in forest fragments in the three forests. The eigenvalue of 0.87 and 0.63 also confirmed that there was a good dispersion of tree species along the first and second ordination axes.

• Most of the DECORANA clusters matched with the TWINSPAN classification, indicating that classification and ordination of tree species data were complementary to each other.

• *T. tiliifolia* showed a higher number of individuals in the adult stage and lesser number of individuals during seedling stage, in the Lower montane forests. In case of *E. fraxinifolia*, density of individuals was more in the seedling stage in Lower montane and Montane forests, whereas in Upper montane forests no individual of this species was encountered. Individuals of *H. latifolia* were also more during seedling stage in all the three forest types. *E. phaseoloides* indicated a growing population in the Lower montane forests with maximum number of individuals in the seedling stage, and all other stages were less prominent.

• *T. tiliifolia* had fair regeneration and *E. fraxinifolia* had good regeneration among the tree species. Among the lianas, both the species (*H. latifolia* and *E. phaseoloides*) had
good regeneration, however the density of *E. phaseoloides* during adult stage was less.

- Seedling populations in all the forests showed marked difference between wet (May-July) and dry (November-March) seasons with more number of tree and liana species in the seedling stage in the wet season. No apparent difference was found in the sapling populations between dry and wet seasons.

- Stump size significantly affected coppice regeneration in *T. tiliifolia*, and *H. latifolia* (*P* < 0.001). Both the tree and liana species did not show variation in sprouting intensity. However, the liana species tend to initiate sprouting at lower girth classes than the tree species. Regression models showing the relationship of stump size with number of sprouts yielded a significant polynomial relationship for above two species (*P* = 0.001).

- *Evodia fraxinifolia* strictly followed a sequential order of one phenological event followed by the other with least overlapping between any two events. In *T. tiliifolia* active vegetative growth, bud formation and flowering initiated more or less at the same phase, particularly during late winter, leaf shedding and seed dispersal also overlapped with each other. In *H. latifolia* leaf flushing occurred during winter season while in *E. phaseoloides* it was prominent during the months of April, May and June till early season of monsoon. Flowering, fruit setting and seed dispersal followed more or less similar sequence in both the species of lianas.

- The number of flower and fruit produced in *Toricellia tiliifolia* was significantly higher (*P* < 0.001) in the year 2008 than in 2006 and 2007. Flower and fruit production varied significantly across DBH classes (*P* < 0.001) and it was higher in higher DBH classes. Flower and fruit production varied significantly across the DBH and forest types (*P* < 0.001). Abortion, flower and fruit production did not show significant variation across the years.
• Size of the soil seed bank for *T. tiliifolia*, *E. fraxinifolia* and *H. latifolia* varied significantly (*P* < 0.001) with girth size. The size of the soil seed bank of *T. tiliifolia* was significantly higher in both the years (2007 and 2008) in the Lower montane forests.

• Seed viability of the selected species decreased consistently across a temporal scale. *H. latifolia*, recorded viability period of almost two years but decreased considerably with time. *E. phaseoloides* and *E. fraxinifolia* recorded viability period of 15 months but that also decreased considerably with time.

• *In situ* seed germination of the liana and tree species varied among different forest types and treatments significantly in relation to litter (*H. latifolia* and *E. fraxinifolia* *P* < 0.001, and in *E. phaseoloides* *P* < 0.05).

• Seedling recruitment for *H. latifolia* was highest in the Montane forests, while, that of *E. fraxinifolia*, it was in the Lower montane forests.

• High seedling mortality of *H. latifolia* occurred during the three months of germination (March-June). Seedling survivorship curves for *E. fraxinifolia* and *E. phaseoloides* showed a sharp reduction in the number of individuals after 3 and 6 months period respectively and continued till the seedlings were one year old, after which the seedling population stabilized.

• The seedling densities of four species were higher in the periphery than in the interior of forest fragments.

• During seedling stage, density was strongly related to soil P for *E. fraxinifolia* and *H. latifolia*, indicating the importance of this factor in seedling establishment. Light intensity and soil pH were positively correlated with seedling density of *T. tiliifolia* species, indicating the role of light only during the juvenile phase of the species.

• Smaller fragment had more or less similar liana density because of similar microenvironment in the interior and along the edges of the fragments.
Based on the response of species as analyzed through eight life history traits, the species were divided into two distinct guilds. *Holboellia latifolia*, *Evodia fraxinifolia* and *Toricellia tiliifolia* were classified as pioneer species, while *Entada phaseoloides* as intermediate to non-pioneer species.