

# Development of Biomass Expansion Factors for Major Conifer Species and Conifer Forests of Bhutan

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## Abstract

Accurate assessment of forest biomass and biomass-related carbon emissions is critical for climate change mitigation, forestry, and REDD+ accounting. An aggregate conifer Biomass Expansion Factor (BEF) of 1.292 was used in compiling Bhutan's Forest Reference Emission Level (FREL) in 2020, but this factor has not been empirically validated. This study estimated species- and size-specific BEFs and Biomass Conversion and Expansion Factors (BCEFs) using destructive sampling data from 357 trees representing eight major conifer species in Bhutan. A Type II analysis of variance (ANOVA) was used to assess the effects of species and 10-cm diameter classes on BEF. The main analysis applied a basal-area-weighted linear model to account for the unequal representation of trees among sampling groups and the greater contribution of larger trees to forest biomass. The weighted model showed a significant effect of species on BEF ( $F_{7,294} = 4.22$ ,  $p < 0.001$ ), whereas diameter class was not significant ( $F_{7,294} = 1.44$ ,  $p = 0.199$ ). A significant species  $\times$  diameter-class interaction was also detected ( $F_{49,294} = 1.57$ ,  $p = 0.013$ ), although this effect was not supported by the unweighted log-transformed sensitivity analysis ( $p = 0.251$ ). The sensitivity analysis nevertheless detected a significant independent effect of diameter class ( $F_{7,294} = 12.64$ ,  $p < 0.001$ ). The aggregate weighted BEF was  $1.292 \pm 0.025$ , closely matching the factor used in Bhutan's FREL. Species-specific BEFs ranged from 1.108 for *Cupressus corneyana* to 1.720 for *Larix griffithii*, while BCEFs ranged from 0.498 to 0.807 Mg m<sup>-3</sup>. Applying the derived BEFs and BCEFs to 2025 wood removals resulted in estimated emissions of 258,193.68 tCO<sub>2</sub>, 25.72% lower than the corresponding FREL estimate, primarily due to differences in wood density. The results support the continued use of the aggregate BEF where species-specific wood-removal data are unavailable, while species-specific BEFs are recommended where such data are available.

**Keywords:** biomass expansion factor, conifer, biomass, wood density

## 1. Introduction

Forests play a vital role in the global carbon cycle (Pan et al., 2024; Vashum & Jayakumar, 2012) by storing 709 billion tonnes of carbon (FRA, 2025) and offsetting nearly half of global fossil-fuel emissions ( $7.8 \pm 0.4 \text{ Pg C yr}^{-1}$  during 1990–2019) (Pan et al., 2024). Thus, accurate estimation of forest biomass is essential for monitoring and understanding forest carbon stocks, emissions, removals and the impact of climate change (Intergovernmental Panel on Climate Change (IPCC), 2026; Vashum & Jayakumar, 2012; Rodríguez-Veiga et al., 2017). Forest biomass is estimated directly through destructive felling and using non-destructive indirect methods such as allometric equations, basic wood densities ( $WD_b$ ), biomass expansion factors (BEF) and biomass conversion and expansion factors (BCEF) (Montès, 2009; Vashum & Jayakumar, 2012; Somogyi et al., 2007; Lehtonen et al., 2004; Soares & Tomé, 2012; Améztegui et al., 2022; Shi & Liu, 2017). Many country-specific, region-specific and species-specific tree allometric equations were developed to estimate the aboveground and belowground biomass using tree attributes such as diameter at breast height (DBH) and height (Améztegui et al., 2022; Soares & Tomé, 2012). At the same time, BEFs,  $WD_b$  and BCEFs are frequently used to convert stand-level volume or forest harvest statistics reported in cubic meter volume to biomass (Améztegui et al., 2022; Soares & Tomé, 2012; IPCC, 2006) as individual tree level measurement such as DBH and height are not always available.

Bhutan has developed species-specific allometric biomass equations for eight conifer species to estimate aboveground biomass and used a BEF of 1.292 in its Forest Reference Emission Level/Forest Reference Level (FREL/FRL). However, this factor has not been validated in any scientific literature. Further, as more disaggregated timber and firewood harvest data at species-level becomes available, the suitability of average BEF factor is not tested.

In addition, the impact of species and tree size on the BEF value has not been evaluated for coniferous trees in Bhutan. Thus, there is a possibility of introducing error due to the assumption of the same BEF for all species and tree sizes when calculating the total aboveground biomass from bole or stem biomass. Previous studies reported over-estimation of forest biomass and carbon with single or default BEF (Sanquetta, Corte & da Silva, 2011; Lee et al., 2018; Li et al., 2023). Similarly, studies reported over-estimation of biomass when air-dried wood densities were applied and recommended using basic wood density for more accurate estimation of biomass (Chave et al., 2006; Reyes et al., 1992; Simpson, 1993; Vieilledent et al., 2018; Huaqiang et al., 2024). Furthermore, IPCC 2006 recommends using BCEF for accounting biomass loss from wood removals and provides default value of  $0.77 \text{ Mg m}^{-3}$  for moist tropical conifer forests with growing stock of more than  $100 \text{ m}^3 \text{ ha}^{-1}$  which is most relevant for Bhutan by global ecological zones (IPCC, 2006). Hence using species-specific BEF,  $WD$  and BCEF are important to improve the accuracy of accounting biomass losses as a result of timber and firewood harvested from forests, which are reported in volumetric units.

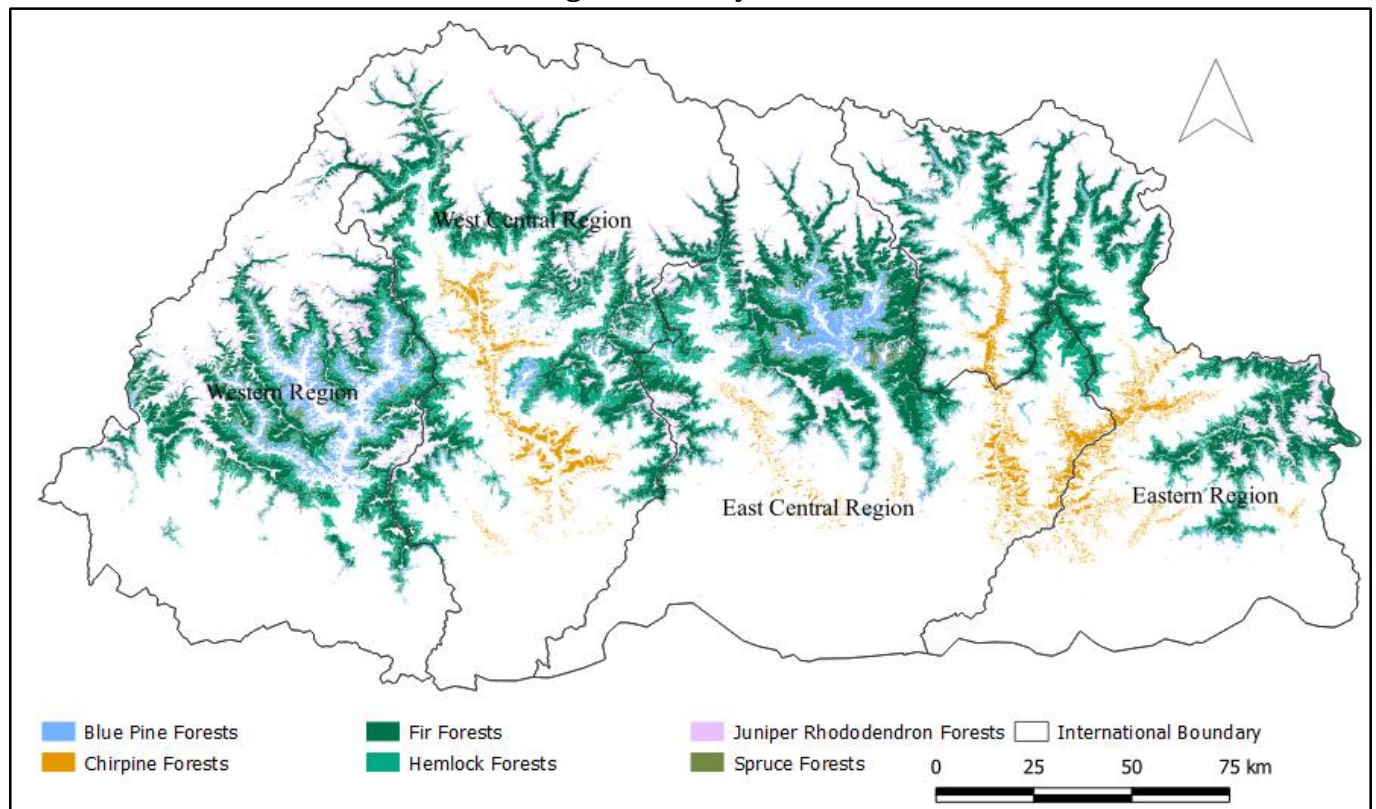
Therefore, the main objectives of this study was to (1) develop species-specific BEF; 2) evaluate variation in BEF among the species and DBH class; 3) determine species-specific biomass conversion and expansion factor; and 4) conduct comparative analysis of emissions from timber and firewood removals using IPCC default factor, factors developed in this study and those used in Bhutan's FREL.

## 2. Materials and Methods

### 2.1 Study Area

The study focuses on eight main conifer species of Bhutan, which constitute dominant tree species in six forest types of Bhutan distributed from 900 - 4200 m above mean sea level (Figure 1). These species constitute main vegetation of six forest types of Bhutan and they are *Pinus roxburghii* (Chir Pine Forest), *Pinus wallichina* (Blue Pine Forest), *Picea spinulosa* (Spruce Forest), *Tsuga dumosa* (Hemlock Forest), *Abies densa* (Fir Forest), *Juniper* spp. (Juniper-Rhododendron Forests) (Grisson & Long, 1983; FMID, 2023). Other two species used in this study *Larix griffithii* and *Cupressus corneyana*<sup>1</sup> which do not constitute a separate forest type and occur as associates in one or more of the six conifer forests (Grisson & Long, 1983).

Figure 1: Study Area



### 2.2 Data Sources

We used the data collected for development of allometric biomass equation for eight conifer species, which comprise of total biomass and bole biomass; country-specific air-dried density (UNIDO, 1994) for four species, basic wood density of three species (*A. densa*, *P. spinulosa*, *J. recurva*) (Chhetri., Wangdi, & Chhetri, 2025), wood density of *Pinus roxburghii* from Nepal (Adhikari et al. 2015) and *Cupressus torulosa* basic wood density of India for *C. corneyana* (Hidayat & Simpson, 1994), as there is no Bhutan specific wood density data for these two species.

<sup>1</sup> In some areas this species is observed to occur as pure stands. However, there is no official record or literature that reports *Cupressus* as a separate forest type.

The biomass data were collected species-wise across the four physiographic zones of Eastern, Western, West Central and Southern Bhutan (Figure 1). A minimum of eight trees were sampled from each physiographic zone making a minimum sample size of the 32 trees per species and where feasible, one tree is selected from 5-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-60 cm, 60-70 cm, and 70-100 cm diameter class at breast height based on the Randomised Branch Sampling (RBS) methodology and manual developed DoFPS (FRMD, 2012). The selected trees were felled, and samples of bole, branches, foliage, dead wood are collected and brought back to the laboratory. All the samples are oven dried at 105° until the constant weight is achieved, and dry weight of samples were computed by components. However, only bole only total biomass and bole biomass is used in this study. In addition, we obtained the timber and firewood harvest statistics for 2025 from the Forest Information Monitoring and Reporting System (FIRMS) managed by the Forest Monitoring and Information Division, Department of Forests and Park Services. The database contains annual statistics of timber and firewood harvested by species for the year 2025.

## 2.3 Biomass Expansion Factor

Biomass Expansion Factor (BEF) is the ratio of total aboveground biomass to stem biomass (Leite Lopes et al, 2025; Li et al., 2010) and tree-level BEF is calculated using Equation 1.

$$BEF = \frac{AGB_{Total}}{BB_{stem}} \quad (\text{Equation 1})$$

Where,

BEF is biomass expansion factor,

AGB<sub>Total</sub> is total aboveground biomass,

BB<sub>stem</sub> is stem biomass. BEF is dimensionless.

Since the BEF depends on the species, forest type, age, density (Petersson et al., 2012; Sanquetta, Corte, & da Silva, 2011), young and smaller trees often have higher BEF than mature trees, due to higher proportion of branches and foliage compared to the stem wood (Petersson et al., 2012; Marziliano et al., 2017). Therefore, basal area weighted BEF was generated to account the contribution of larger trees on overall biomass allocation (Poorter et al., 2015). The weighted BEF is estimated using Equation 2.

$$BEF_w = \frac{\sum(ba \cdot BEF)}{\sum ba} \quad (\text{Equation 2})$$

Where,

BEF<sub>w</sub> is a weighted biomass expansion factor;

ba is basal area (m<sup>2</sup>) of an individual tree;

BEF is biomass expansion factor of individual tree;

Σ(ba . BEF) is sum of product of ba; and BEF, Σ ba is the sum of basal areas of all sample trees.

Subsequently, we computed the standard weighted standard deviation and standard error using Equations 3 and 4.

$$SD_w = \sqrt{\frac{\sum ba * (BEF - BEF_w)^2}{\sum ba}} \quad (\text{Equation 3})$$

$$SE_w = \frac{SD_w}{\sqrt{n}} \quad (\text{Equation 4})$$

Where,

$SD_w$  is weighted standard deviation;

$ba$  is basal area ( $m^2$ );

BEF is biomass expansion factor of individual tree;

$BEF_w$  is weighted mean biomass expansion factor; and  $SE_w$  is weighted standard error and  $n$  is sample size.

## 2.4 Basic Wood Density ( $WD_b$ ) and Biomass Conversion and Expansion Factor

We adopted the air-dried densities of *P. spinulosa*, *L. griffithii*, *P. wallichiana*, *T. domusa* from UNIDO (1994); basic wood density of *A. densa*, *P. spinulosa*, *J. recurva* from Chhetri et al. (2025) and basic wood density of *P. roxburghii* from Nepal (Adhikari et al. 2015) and adopted the basic density of *C. torulosa* for *C. corneyana* from India (Hidayat & Simpson, 1994) as they are taxonomically associated and there is no published data on wood density of *C. corneyana* in Bhutan or elsewhere. Air-dried wood density was converted to basic wood density using the Reyes model (1992), Equation 5, which is reported to be more suitable than other models such as Huaqiang et al. (2024), Vieilledent et al. (2018), Chave (2006) and Simpson (1993) based on a comparative analysis carried out by Huaqiang et al. (2024).

$$WD_b = 0.800WD_a + 0.0134 \quad (\text{Equation 5})$$

Where,

$WD_b$  is basic wood density ( $g\ cm^{-3}$ ); and

$WD_a$  is air-dried wood density ( $g\ cm^{-3}$ )

Using the basic wood density and BEF, we estimated BCEF using equation 6 based on the 2006 IPCC Guidelines (IPCC, 2006).

$$BCEF = BEF \times WD_b \quad (\text{Equation 6})$$

Where, BCEF is a biomass conversion and expansion factor;

$BEF_w$  is weighted biomass expansion factor; and

$D_b$  is basic wood density

## 2.5 CO<sub>2</sub> Emissions from Timber and Firewood

To compare the biomass loss or emission from the timber and firewood harvest, we estimated the emission using the standard IPCC accounting approach. The volume of timber and firewood was converted into biomass using the derived BEF, WD and BCEFs. Subsequently, Biomass is converted to carbon using a carbon fraction of 0.47, and to CO<sub>2</sub> using the molecular weight ratio 44/12. Results are then compared with estimates obtained using IPCC default BEF/BCEF values to assess differences and potential bias in the estimated emission from the forest disturbance, particularly wood removals.

## 2.6 Data Analysis

The data analysis is performed in the r statistical package and r-studio and the microsoft excel. A total of 357 individual tree samples consisting *Abies densa* (n= 55), *Cupressus corneyana* (n= 32) *Junipersus recurva* (n= 32), *Larix griffithii* (n= 32), *Picea spinulosa* (n= 48), *Pinus roxburghii* (n=51), *Pinus wallichina* (n= 52) and *Tsuga dumosa* (n=55). The species are grouped into eight DBH Classes; <10 cm, 10-20 cm, 20-30cm, 30-40 cm, 40-50cm, 50-60 cm, 60-70 cm, and >=70 cm. Statistical analyses were conducted to estimate mean BEF of all samples, species and DBH class, and accordingly, mean values of the BCEF were determined based on the mean values of the BEF. Uncertainty was expressed using standard errors, and results were compared with IPCC default and previously used factors.

We examined whether BEF differed among tree species and DBH classes using Type II analysis of variance (ANOVA). Because the number of trees was not the same for all species and DBH classes, Type II ANOVA was used to account for the unequal sample sizes. For the main analysis, we used a weighted linear model, with tree basal area used as the weight. This gives greater importance to larger trees when estimating the overall pattern of BEF. The model included species, DBH class, and their interaction:

$$\text{BEF} \sim \text{Species} + \text{DBH class} + \text{Species} \times \text{DBH class (Model- 1)}$$

The interaction term was included to determine whether the effect of tree size on BEF differed among species.

In addition a sensitivity analysis was performed using the log-transformed BEF without weighting. This analysis was necessary to check whether the results from the main analysis were affected by the weighting of trees or by the scale of BEF. The sensitivity model included species and DBH class:

$$\ln(\text{BEF}) \sim \text{Species} + \text{DBH class [Model -2]}$$

The species  $\times$  DBH class interaction was not included in this model because it was not significant after log transformation.

## 3. Results

### 3.1 Biomass Expansion Factors (BEFs)

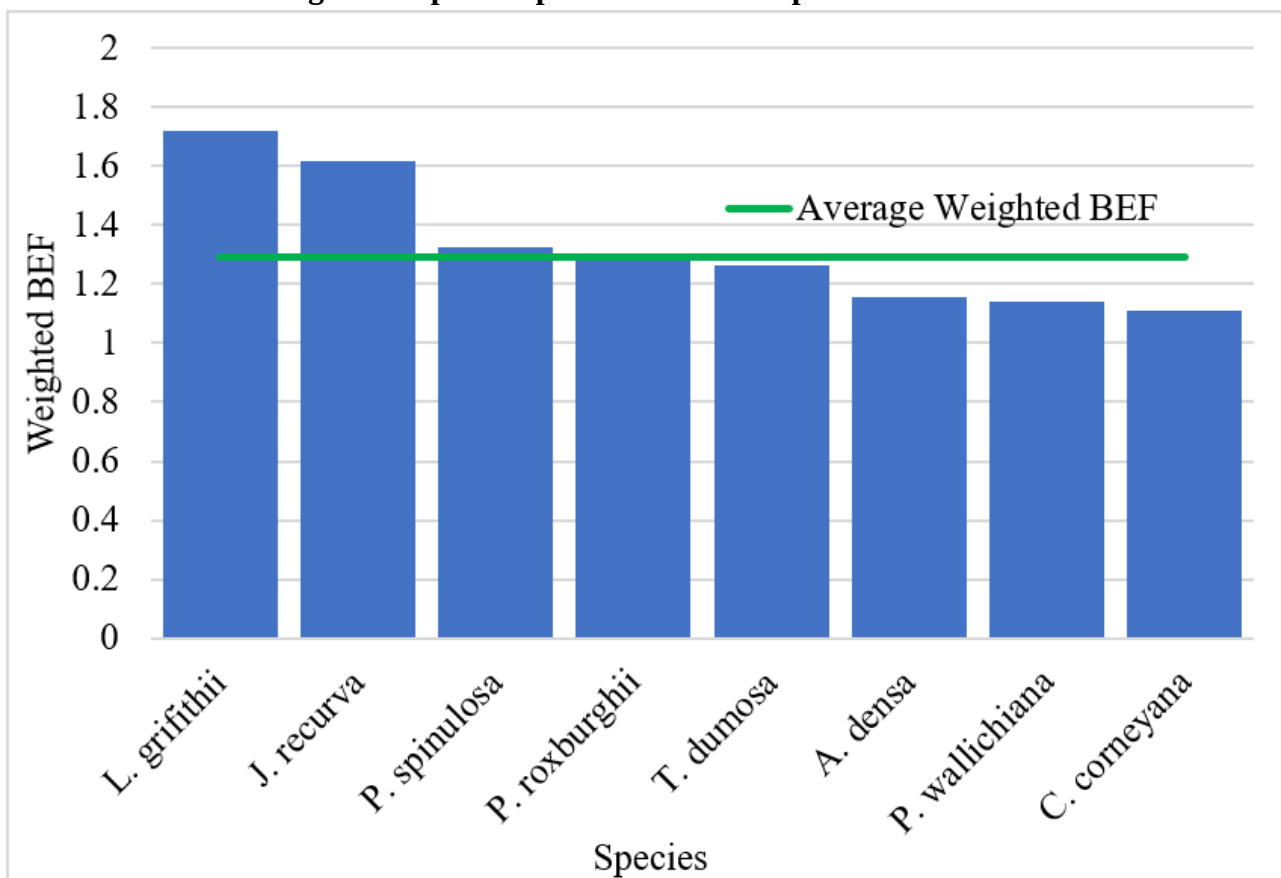
The calculated BEFs for conifer species showed moderate variability across species. The overall mean BEF was  $1.403 \pm 0.031$  (SE) while the weighted BEF was  $1.292 \pm 0.025$ . Individual species weighted BEF ranged from 1.108 to 1.721, reflecting differences in crown structure, branching patterns, and biomass allocation. Table 1 shows the comparison of BEF, weighted BEF (Figure 2), basic wood density and BCEF. The average basic wood density is  $0.4212 \text{ t m}^{-3}$  while BCEF is  $0.544 \text{ t m}^{-3}$ .

**Table 1: Biomass Expansion Factor, Basic Wood Density, Biomass Conversion and Expansion Factors**

| Species | n | Mean BEF | SE | BA-weighted BEF | Weighted SE | Basic density (t m <sup>-3</sup> ) | BCEF (t m <sup>-3</sup> ) |
|---------|---|----------|----|-----------------|-------------|------------------------------------|---------------------------|
|         |   |          |    |                 |             |                                    |                           |

|                     |    |       |       |       |       |        |        |
|---------------------|----|-------|-------|-------|-------|--------|--------|
| Abies densa         | 55 | 1.249 | 0.039 | 1.154 | 0.021 | 0.432  | 0.499  |
| Cupressus corneyaya | 32 | 1.248 | 0.082 | 1.108 | 0.016 | 0.437  | 0.484  |
| Juniperus recurva   | 32 | 1.499 | 0.077 | 1.615 | 0.096 | 0.4094 | 0.661  |
| Larix grifithii     | 32 | 1.816 | 0.193 | 1.720 | 0.208 | 0.4054 | 0.697  |
| Picea spinulosa     | 48 | 1.434 | 0.076 | 1.323 | 0.047 | 0.3424 | 0.453  |
| Pinus roxburghii    | 51 | 1.501 | 0.108 | 1.284 | 0.045 | 0.533  | 0.0685 |
| Pinus wallichiana   | 52 | 1.232 | 0.031 | 1.141 | 0.013 | 0.4254 | 0.485  |
| Tsuga dumosa        | 55 | 1.394 | 0.055 | 1.262 | 0.030 | 0.3846 | 0.485  |
| Mean                |    | 1.403 | 0.031 | 1.292 | 0.025 | 0.4212 | 0.544  |

**Figure 2: Species-specific Biomass Expansion Factors**



### 3.2 Variation across DBH classes

BEF varied considerably among diameter classes for all species (Table 2). Trees of small diameter (less than 10 cm) tended to have larger BEFs, probably due to a higher percentage of branch and foliage biomass compared to stems. With an increase in diameter, the BEF declined gradually and converged to a stable value, possibly because of the dominance of stem biomass in large trees. Overall, the mean BEF for trees with DBH of < 10 cm was as high as  $1.740 \pm 0.096$ , whereas the trees with DBH of > 70 cm had a BEF of only  $1.190 \pm 0.030$ .

**Table 2: BEF Variation Across DBH Class All Species Combined**

| DBH Class (cm) | No. of samples | Unweighted BEF | Unweighted BEF SE | Weighted BEF | Weighted BEF SE |
|----------------|----------------|----------------|-------------------|--------------|-----------------|
| <10            | 54             | 1.812          | 0.118             | 1.74         | 0.096           |
| 10-20          | 47             | 1.463          | 0.045             | 1.448        | 0.041           |
| 20-30          | 49             | 1.333          | 0.064             | 1.35         | 0.068           |
| 30-40          | 48             | 1.254          | 0.042             | 1.254        | 0.041           |
| 40-50          | 48             | 1.334          | 0.082             | 1.327        | 0.08            |
| 50-60          | 47             | 1.414          | 0.112             | 1.41         | 0.108           |
| 60-70          | 33             | 1.259          | 0.065             | 1.265        | 0.066           |
| 70+            | 31             | 1.185          | 0.029             | 1.19         | 0.03            |

DBH and BEF did not show a linear relationship, BEF declined sharply from the smallest classes through 30–40 cm, increased in the 40–60 cm classes, and declined again in the largest trees. Further, the trends are not similar among the species (Table 3).

**Figure 3: Basal-area-weighted BEF across DBH classes with standard error**

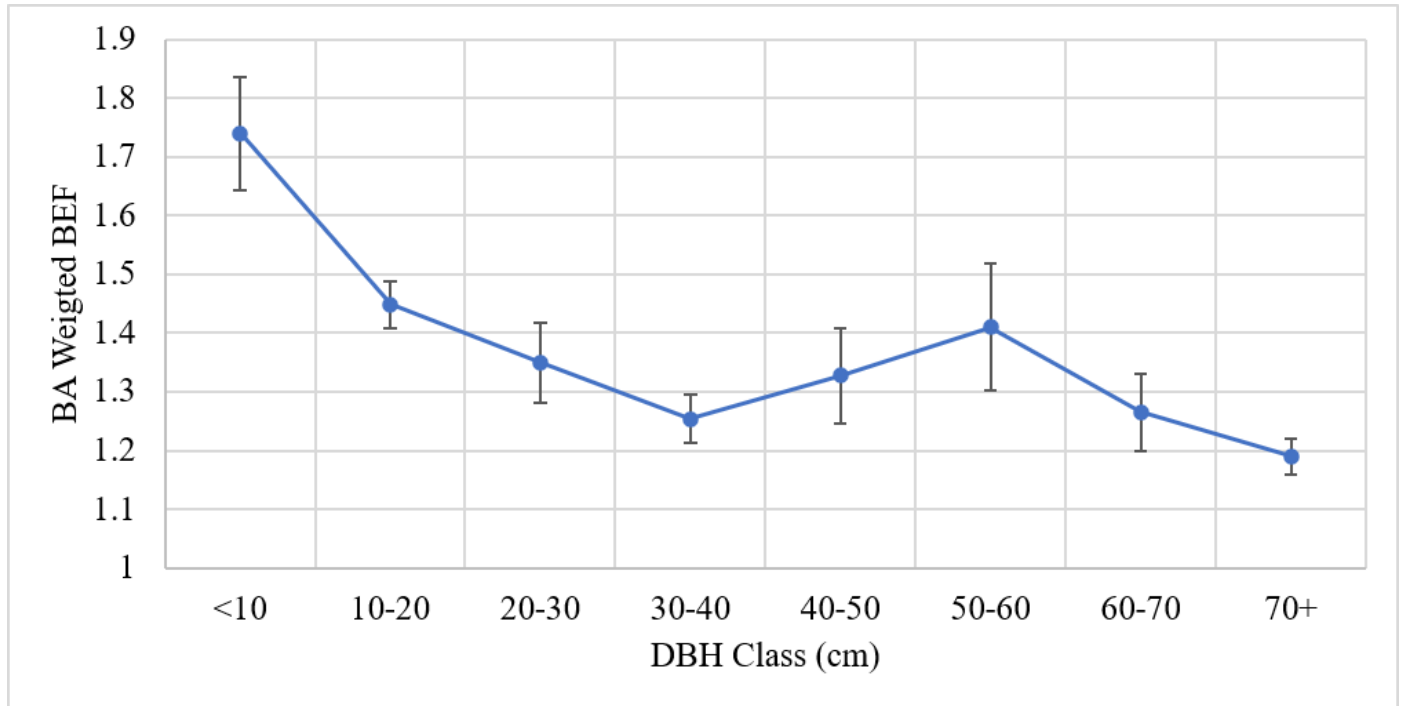


**Table 3: Basal Area Weighted BEF Across the Species and DBH Class**

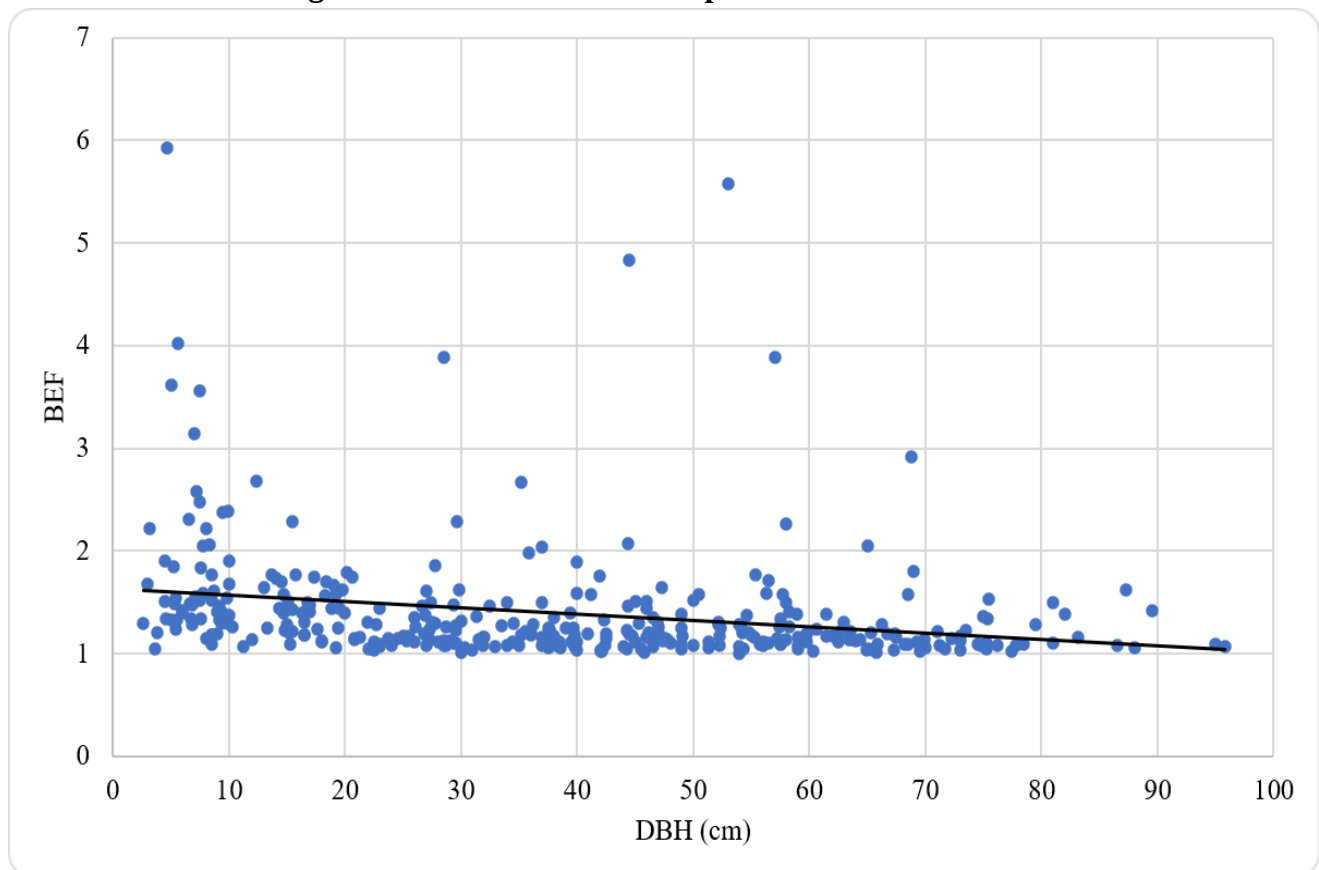
| Species/DBH Class  | <10           | Oct-20        | 20-30         | 30-40         | 40-50         | 50-60         | 60-70         | 70+           |
|--------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Abies densa        | 1.608 ± 0.145 | 1.522 ± 0.17  | 1.233 ± 0.091 | 1.112 ± 0.013 | 1.165 ± 0.062 | 1.15 ± 0.035  | 1.11 ± 0.025  | 1.163 ± 0.101 |
| Cupressus corneyay | 1.698 ± 0.335 | 1.327 ± 0.115 | 1.083 ± 0.018 | 1.094 ± 0.028 | 1.08 ± 0.004  | 1.117 ± 0.05  | 1.136 ± 0.014 | 1.086 ± 0.019 |
| Juniperus recurva  | 1.506 ± 0.049 | 1.517 ± 0.192 | 1.347 ± 0.087 | 1.252 ± 0.032 | 1.448 ± 0.158 | 1.699 ± 0.186 | 1.912 ± 0.443 | 0 ± 0         |
| Larix griffithii   | 2.658 ± 0.413 | 1.62 ± 0.062  | 1.357 ± 0.098 | 1.27 ± 0.078  | 2.113 ± 0.6   | 2.476 ± 0.646 | 1.111 ± 0.026 | 1.164 ± 0.006 |
| Picea spinulosa    | 1.65 ± 0.277  | 1.328 ± 0.047 | 1.482 ± 0.135 | 1.464 ± 0.25  | 1.329 ± 0.078 | 1.142 ± 0.016 | 1.449 ± 0.242 | 1.303 ± 0.143 |
| Pinus roxburghii   | 1.729 ± 0.324 | 1.515 ± 0.079 | 1.774 ± 0.414 | 1.395 ± 0.132 | 1.234 ± 0.05  | 1.348 ± 0.081 | 1.237 ± 0.067 | 1.174 ± 0.081 |
| Pinus wallichiana  | 1.601 ± 0.155 | 1.35 ± 0.069  | 1.135 ± 0.025 | 1.181 ± 0.037 | 1.141 ± 0.02  | 1.131 ± 0.016 | 1.128 ± 0.036 | 1.133 ± 0.036 |

|                 |                  |                  |                  |                  |                  |                 |                  |                  |
|-----------------|------------------|------------------|------------------|------------------|------------------|-----------------|------------------|------------------|
| Tsuga<br>dumosa | 2.012 ±<br>0.231 | 1.459 ±<br>0.081 | 1.247 ±<br>0.036 | 1.365 ±<br>0.123 | 1.205 ±<br>0.067 | 1.27 ±<br>0.081 | 1.247 ±<br>0.138 | 1.257 ±<br>0.056 |
|-----------------|------------------|------------------|------------------|------------------|------------------|-----------------|------------------|------------------|

The type II ANOVA test statistical results showed that the species has a statistically significant effect on BEF ( $F_{7, 294} = 4.22$ ,  $p < 0.001$ ) while DBH Class has no significant effect on the BA weighted linear model ( $F_{7, 294} = 1.44$ ,  $p = 0.199$ ). The species  $\times$  DBH interaction was significant ( $F_{49, 294} = 1.57$ ,  $p = 0.013$ ). However, this significance was not supported by the log-transformed sensitivity analysis.

In the unweighted log-BEF sensitivity model, species remained significant ( $F_{7, 294} = 5.79$ ,  $p < 0.001$ ), DBH class was significant ( $F_{7, 294} = 12.64$ ,  $p < 0.001$ ), and the species  $\times$  DBH interaction was not significant ( $F_{49, 294} = 1.14$ ,  $p = 0.251$ ). The sensitivity analysis therefore strengthens the conclusion that species differences are robust but shows that inferences about the detailed DBH response depend on the analytical scale and weighting.

**Figure 4: Tree-level relationship between DBH and BEF**



### 3.3 Comparison with existing factors

The comparison of factors developed in this study and the existing factors, used during the development of Bhutan's FREL/FRL (BEF = 1.292 for conifers) and IPCC default factors are presented in Table 4. Our aggregated BEF is  $1.292 \pm 0.025$ , which is approximately equal to the existing factor for conifer forests used actually in Bhutan's FREL/FRL, which confirms its correctness on the aggregated level, but

significantly varies for particular species, for instance, *Larix griffithii* BEF is 1.721. On the other hand, the wood density used in the FREL/FRL is higher than the average basic wood density derived and adopted in thai study, which indicates that biomass from the timber and firewood might have been overestimated based on our findings.

**Table 4: Comparison of BEF and BCEF Values with Existing Factor**

| Source              | WD (t m <sup>-3</sup> ) | BEF             | BCEF (Mg m <sup>-3</sup> ) | Application                 |
|---------------------|-------------------------|-----------------|----------------------------|-----------------------------|
| FREL/FRL (2020)     | 0.483                   | 1.292 (conifer) | —                          | National accounting         |
| IPCC Default (2006) |                         | 1.3–1.5         | 0.77                       | Tropical/subtropical        |
| Weighted Average    | 0.4212 ± 0.019          | 1.292 ± 0.025   | 0.544± 0.037               | Species-specific/This study |

### 3.4 CO<sub>2</sub> Emissions from Wood Removal

Using the species-specific BEF and basic wood density from this study, CO<sub>2</sub> emissions from timber and firewood harvesting for the year 2025 was 258,193.68 tonnes (Table 5). This value is 25.72 % lower than those calculated using BEF and wood density from FREL and 39.80% lower than IPCC default BCEF. The estimated emissions at species level from factors developed in this study was also lower than FREL and IPCC default for all the species, except *Juniper recurva* and *L.griffithii*.

**Table 5: Comparison of emissions from Conifer timber and firewood harvested in 2025 (tCO<sub>2</sub>)**

| Species                    | FREL     | IPCC default | This study | FREL vs This study | IPCC vs This study |
|----------------------------|----------|--------------|------------|--------------------|--------------------|
| <i>Abies densa</i>         | 11065.08 | 13653.23567  | 8848.006   | 20.04%             | 35.19%             |
| <i>Cupressus corneyana</i> | 243.6573 | 300.6495107  | 188.97969  | 22.44%             | 37.14%             |
| <i>Juniperus recurva</i>   | 1507.372 | 1859.95079   | 1596.6591  | -5.92%             | 14.16%             |
| <i>Larix griffithiana</i>  | 190.2282 | 234.7231528  | 212.47018  | -11.69%            | 9.48%              |
| <i>Picea spinulosa</i>     | 50288.75 | 62051.4494   | 36505.593  | 27.41%             | 41.17%             |
| <i>Pinus roxburghii</i>    | 18412.04 | 22718.6765   | 2021.0771  | 89.02%             | 91.10%             |
| <i>Pinus wallichiana</i>   | 69030.73 | 85177.23789  | 53650.598  | 22.28%             | 37.01%             |
| <i>Tsuga dumosa</i>        | 173793.2 | 214444.0328  | 135071.89  | 22.28%             | 37.01%             |
| Other Conifers             | 23055.38 | 28448.10986  | 20098.405  | 12.83%             | 29.35%             |

|       |          |             |           |        |        |
|-------|----------|-------------|-----------|--------|--------|
| Total | 347586.5 | 428888.0656 | 258193.68 | 25.72% | 39.80% |
|-------|----------|-------------|-----------|--------|--------|

## 4. Discussion

### 4.1 BEF Differences Among the Species

The species-specific BEF values estimated in this study ranged from 1.108 to 1.721, indicating large interspecific variability (Table 1). This variation is consistent with differences in crown development, branching, stem form and allocation of biomass among tree components. The species-specific BEF values are within the range reported for temperate and subtropical conifers (Lehtonen et al., 2004; Zianis & Mencuccini, 2004). The average basal area weighted BEF of 1.292 is almost identical to BEF for conifers used for FREL/FRL and indicates that the BEF used in REDD+ emission accounting is accurate at the aggregated level. This finding supports using BEF of 1.292 at the aggregate level, and species-specific BEF may be used when using the species activity data or when such data becomes available. However, allometric equations should be used when tree-level measurements such as DBH and height are available, as they produce more accurate estimates than the BEF (Marziliano et al., 2017; Setiahadi, 2021).

### 4.2 DBH-Dependent BEF Patterns

The observed decline in BEF with increasing DBH is consistent with the fundamental biomass allocation theory (Enquist et al., 2007; Poorter et al., 2012). Small trees have higher BEF due to the need to allocate more biomass to branches and foliage for resource capture, while larger trees reduce BEF by allocating more biomass to stems for height growth (Gower et al., 2001). The observed BEF pattern declined from 1.74 (for DBH < 10 cm) to 1.190 (for DBH > 70 cm). This trend is consistent with the size-dependent forest BEF reported by Chave et al. (2006) and demonstrates overall phenotypic growth forms.

On the other hand, we did not detect a significant overall effect of dbh class on the weighted primary model. While the model showed a significant species-DBH interaction, the log-transformed BEF sensitivity analysis did not support the finding, and could be attributed to the unbalanced sample design. Thus, these results do not provide a sufficiently stable basis for introducing separate species × DBH factors into national accounting.

### 4.3 Wood Density and BCEF

The basic wood densities were not available for all species and were derived from the air-dried density for three species, while basic wood density for *P. roxburghii* and *C. corneyana* are adopted from Nepal and India respectively. The average wood density of 0.4212 Kg m<sup>-3</sup> is lower than the average wood density used in FREL (0.483 t m<sup>-3</sup>), which is based on the average wood density of four conifer species based on UNIDO (1994). Further, the BCEF derived from BEF and WD is useful for converting the timber and firewood harvest volumes into biomass. More accurate estimation of the BCEF could be derived using the compatible stem volume as denominator since BCEF used with removal statistics must correspond to the volume definition used in the statistics. Further, the BCEF computed in this study 0.544 t m<sup>-3</sup> is less than the IPCC default value of 0.77 t m<sup>-3</sup> applicable for Bhutan. Thus, unless better estimates of WD and BCEF

are available, this study recommends using WD and BCEF derived in this study for future REDD+ and GHG accounting purposes.

#### 4.4 Implications for Carbon Accounting

The species-specific BEF and BCEF obtained in this study have key implications for Bhutan's national GHG inventory reporting and REDD+ implementation. Accurate estimation of emissions from the removal of wood is critical for:

**National reporting:** Since Bhutan reports to the UNFCCC on its greenhouse gas emissions, which involve forest degradation, the application of species-specific BEF and BCEF obtained in this study will improve accuracy and reduce uncertainties.

**Results-based payment:** For results-based payment for REDD+, emission estimates determine the amount of compensation; therefore, both overestimated and underestimated values can negatively affect the country's economy.

**Improved forest management:** Emission estimates will also help the country to have accurate figures for biomass when formulating forest management plans.

While the species-specific BEF, WD and BCEF can improve the accuracy of the estimates, their use should be integrated **with** allometric equations. Where available, allometric equations may include the trees harvested for timber and firewood if the species identity, DBH and height information are available. BEFs and BCEFs are useful where the activity data are available only as volume.

For future national accounting, field validation should include direct measurement of stem volume on the same trees used for destructive biomass sampling. This would permit direct validation of BCEF against the actual volume definition used in timber and fuelwood statistics. It would also allow uncertainty to be propagated from biomass measurements, wood density, BEF, BCEF and activity data into the final CO<sub>2</sub> estimates.

#### 4.5 Limitations and Future Research

Several limitations in this study should be noted. First, this study had a small sample size for some species such as *Larix griffithii* and *Juniperus recurva*, and therefore there is a possibility that the BEF for these species might be underestimated. Second, this study only considered the biomass component found in the aboveground part of the tree. Lastly, the study used wood density values recorded in other databases for some species rather than directly measured values.

Future studies can expand on this research by: (1) considering a larger sample size for all species; (2) determining the BCEF for broadleaved species and forest; (3) determining the BEF temporal trends through repeat measurements; and (4) developing a complete framework for carbon accounting that considers both the aboveground biomass component and belowground components such as the soil.

#### 5. Conclusion

This study determined the biomass expansion factors for eight conifer species found in Bhutan. The overall weighted BEF of  $1.292 \pm 0.025$  estimated supports the currently used FREL factor of 1.292 at the

aggregate level. However, there were large variations in BEF for the different species, ranging from 1.108 to 1.720. This implies that even though the application of BEF might be appropriate at the aggregate level in national inventory calculations, BEF for each species should be used at the species level for more accurate estimates. Additionally, this study established that BEF is strongly influenced by the species, while impact of DBH is not statistically significant. Therefore, where possible, wood removal statistics should be maintained by species and decreased significantly with the increase in DBH; therefore, the use of size-specific BEF is recommended for accurate biomass estimates of wood removed from forests. Further, the species-specific BCEFs that were calculated can improve emission estimates for timber and fuelwood in Bhutan.

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## Data Availability

The data supporting the findings of this study are available from the corresponding author upon request. Species-specific BEF and BCEF estimates are provided in tables within this manuscript.



## Acknowledgements

The authors thank the Department of Forests and Park Services, Royal Government of Bhutan, for providing access to inventory data, as well as the field technicians and staff at the laboratory who assisted in this work.