A study on general allometric relationships developed for biomass estimation in regional scale taking the example of *Tectona grandis* grown in Bundelkhand region of India

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In this communication an effort has been made to develop a general non-site specific allometric relationship taking *Tectona grandis* grown in semi-arid Bundelkhand region without harvesting any tree. To determine the most appropriate predictor variable for producing the relationship, different physiological parameters of this tree species like diameter at breast height (dbh), basal diameter, tree height, forking height, collar diameter, etc. were collected from the standing trees from MP part of Bundelkhand region, comprising a total of 45 sites of 4 districts namely Guna, Vidisha, Chhatarpur and Tikamgarh. The dataset contained 418 trees with biomass ranging from 12.79 kg/tree to 12707.92 kg/tree, height ranging from 1.5 to 18.5 m and dbh ranging from 0.03 to 0.44 m. For developing the models; dbh, height, dbh × height and dbh^2 × height were used as predictor variables. All four contrasting sites were taken for developing allometric models and after examining model residuals and site-specific relationships, it was found that using dbh^2 × height alone as the predictor variable produced the most stable model. Thus it makes regional estimation of aboveground biomass production easier with precision as accurate as site-specific allometry.

Keywords: Allometry, Bundelkhand region, normalized difference vegetation index, residual diagnostics, *Tectona grandis.*

ESTIMATION of forest carbon sequestration, carbon trading schemes are nowadays of utmost importance. It requires reliable and general non-site specific allometric relationship using which we can convert the inventory data of any forest area to regional scale estimate of biomass production. In this regard, allometric relationships, i.e. equations relating an easily measurable variable to its aboveground biomass can be used in experimental basis to estimate its total biomass. When we consider trees in a population scale we can find that their dimensions are statistically correlated[1]. This is the basic principle of tree allometry and can be used to predict any tree variable, particularly tree biomass with the help of other tree variables. An allometric model is a formula that quantitatively formalizes the relationship. If we have general non-site specific biomass equation of a particular tree species, it becomes cost effective to estimate the total biomass at different sites across the geographical range of the same tree species. Studies are available that calculate biomass for multispecific and uneven-aged stands, but the problem with them was that their conversion to equations was not possible[2]. Matrix population models were developed for trees divided into different functional groups according to their growth strategy and into classes of homogenous dimension[3–5]. When modelling is based on individual tree to map the tree population, it was shown that the growth of a given tree depends on its neighbour[6]. In the present study different tree physiological parameters and their combinations are used as predictor variables for biomass estimation as earlier study suggested the inclusion of tree height and/or tree wood density to account for the site factor[7,8] during modelling tree total biomass. Till date, most of the studies have concentrated on developing site-specific tree biomass equations and less efforts were made to combine the data collected from several sites for a particular tree species to develop a general non-site specific biomass equation. In this paper, the variations in different biomass equations of contrasting sites have been examined considering one tree species, i.e. *Tectona grandis.*

The study area is located in the Central Highland physiographic zone of Madhya Pradesh, between 21°17′–26°52′N lat. and 74°08′–82°49′E long. The dataset is a subset of the data collected in National Carbon Project (NCP) under Geosphere–Biosphere Program (I-GBP) by ISRO/DOS to assess the terrestrial vegetation carbon pool in the country using satellite remote sensing data and ground sampling. It contains different biometric characters of tree species located in northwestern part of Madhya Pradesh (MP). In the present study, teak (*Tectona grandis*) was considered for estimation in four districts of MP. A total of 45 sites were selected from 4 districts for the collection of data, viz. Guna (17 sites), Vidisha (10 sites), Chhatarpur (10 sites) and Tikamgarh (8 sites) using normalized difference vegetation index (NDVI) map based on IRS-P6 LISS3 imagery (Figure 1). For sampling design and identification of sampling sites, the strata considered are forest types based on DOS and ISRO studies, forest density based on Forest Survey of India (FSI), and NDVI based on AWiFS. Sample plots were laid down in different homogeneous strata on the basis of NDVI values provided by National Remote Sensing Centre (NRSC). Four plots, each of 0.1 ha in size were selected for collection of tree samples. The spatial resolution of AWiFS was 56 m and the plot size was 31.61 × 31.61 m, thus one pixel covered nearly four plots[9]. Four plots of 0.1 ha size were identified in each site. Nested two-stage sampling approach was adopted for sampling of trees (0.1 ha), shrubs (25 m^2) and herbs (1 m^2) (Figure 2). Indian laws do not permit cutting or

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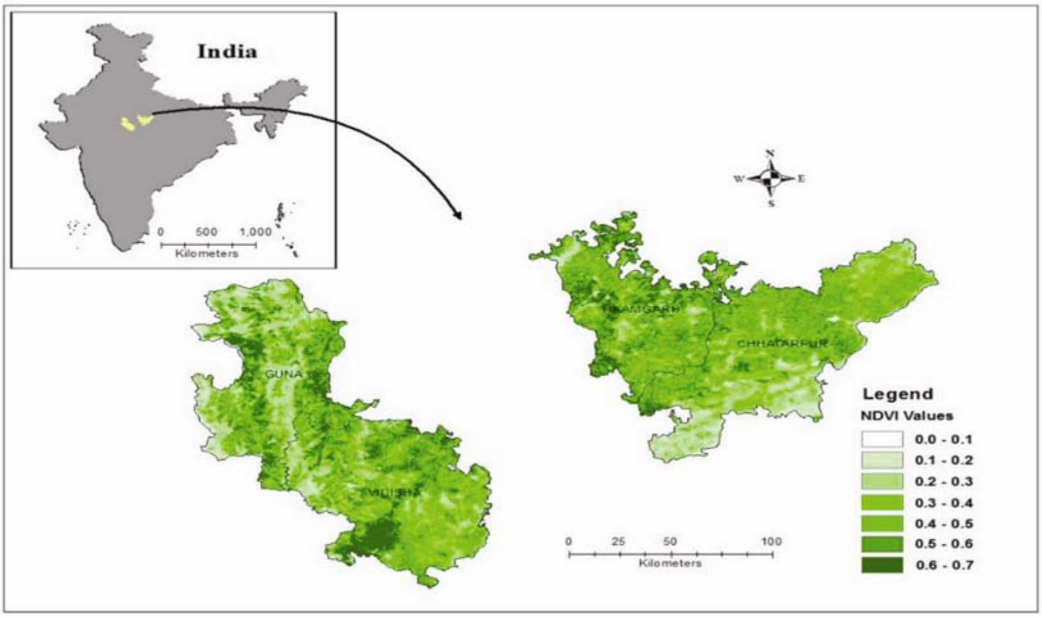

Figure 1. NDVI map of the study area.

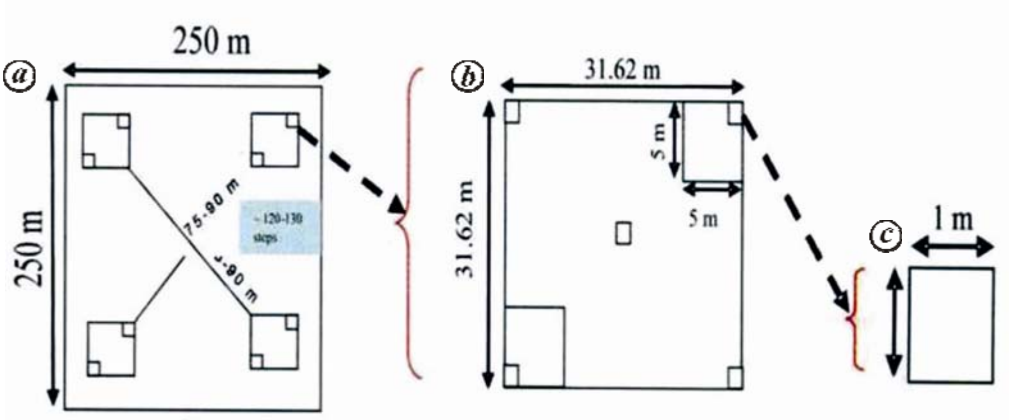

Figure 2. Clustering 2-stage sampling (***a***) 250 × 250 m site for four quadrats, (***b***) sample of trees (0.1 ha), shrubs (25 m^2) and (***c***) herbs (1 m^2).

harvesting any plants, so direct or destructive method of estimating biomass was difficult. Therefore indirect or non-destructive method was the only alternative left for biomass estimation by combination of visual or assumption methods. So, volume over bark value of different parts of the standing tree were separately calculated to achieve total volume over bark value of the standing tree by adding them. A total of 418 teak trees were sampled and data on several physiological parameters like DBH, basal diameter, tree height, forking height, collar diameter, etc. were collected. Then geometric relationships were used to approximate the volume of standing tree bole. The algebraic formulae were applied as empirical analyses often indicate that the volume of a single-stemmed tree is between that of a cone and a cylinder, with tree volume often lying between 0.40 and 0.45 times that of an equivalent cylinder. Using a value of 0.42 for example, an equation can be developed to estimate cubic volume of wood[10]. Then the total volume over bark of the standing tree bole was calculated by adding the volume of these different parts. The stem wood biomass was calculated by multiplying volume with wood density of *Tectona grandis*[11]. The stem wood biomass was then expanded to total above ground biomass of tree including leaves, twigs, branches, bole and bark using biomass expansion factor (BEF)[12].

$$\text{Total above ground biomass} = \text{Stem wood volume} \times \text{wood density} \times \text{BEF}.$$

The mean BEF value of 1.5 was used for this study[13]. The below ground biomass was calculated by using simple

Table 1. Descriptive statistics of the sample trees collected

	Maximum	Minimum	Mean	Variance	SW
Guna (*n* = 63)					
DBH (m)	0.24	0.06	0.09	0.0013	0.9213**
Height (m)	6.5	1.5	4.23	0.951	0.9627*
Total biomass (kg)	1312.79	13.94	160.53	37,259.26	0.6428**
Vidisha (*n* = 235)					
DBH (m)	0.29	0.07	0.14	0.01	0.9453**
Height (m)	17.50	4.00	7.75	8.21	0.275**
Total biomass (kg)	4182.97	18.29	785.93	824,240.40	0.786**
Tikamgarh (*n* = 51)					
DBH (m)	0.39	0.07	0.24	0.01	0.8899**
Height (m)	12.70	2.10	8.21	12.74	0.8484**
Total biomass (kg)	6193.17	17.44	2424.74	3,100,799	0.9284*
Chhattarpur (*n* = 69)					
DBH (m)	0.44	0.08	0.11	0.0079	0.7365**
Height (m)	18.50	2.30	6.23	17.79	0.8148**
Total biomass (kg)	12,707.92	12.79	799.37	4295309	0.4071**
General (*n* = 418)					
DBH (m)	0.44	0.06	0.13	0.0067	0.9043**
Height (m)	18.50	1.50	7.02	10.93	0.9427**
Total biomass (kg)	12,707.92	12.79	893.84	1,916,210	0.6427**

$^*P < 0.05$, $^{**}P < 0.01$.

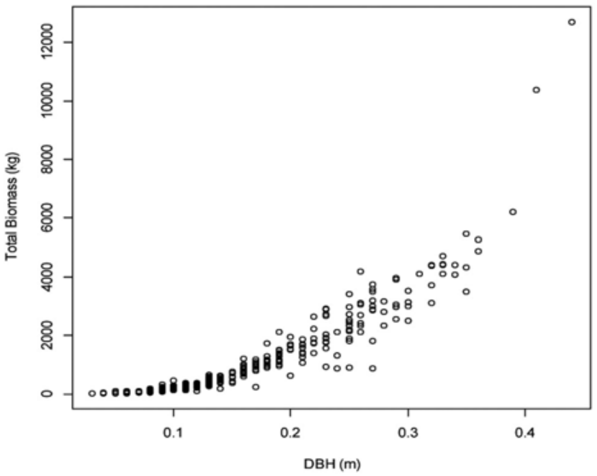

Figure 3. Scatterplot between total biomass and DBH.

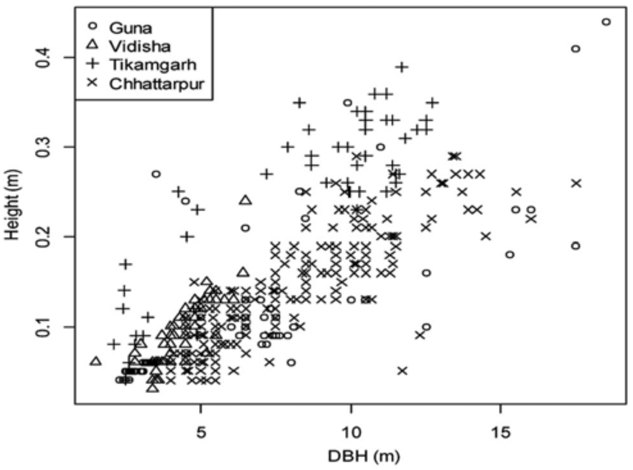

Figure 4. The relationship between tree height and DBH depending on different contrasting sites.

default value of 25% (for hardwood species) of the total above ground biomass[14].

In this study the statistical analysis has been restricted to the most common allometric form[15] to analyse the relation between total biomass production to other tree physiological parameters. The model fitting using regression procedure was performed using *R* (3.0.3) statistical software and the parameters were estimated using ordinary least square method[16]. The model with highest R^2 and minimum root mean square error (RMSE) was selected for testing and validation. Several model diagnostics or statistical validation techniques were followed for the selection and assessment of final selected model.

As the variability of biomass always increases with the increase in tree DBH, a linear model of biomass against DBH was first tried

$$\text{Total biomass} = a_0 + a_1\text{DBH} + \in.$$

But during graphical exploration of the available data, it was found that dependent variable (total biomass) varies/increases with independent variable (DBH) (Figure 3) which showed the symptom of non-constant variance in biomass. So the model mentioned above cannot be fitted using linear regression. The log transformation stabilized the variance and the model became

$$\ln(\text{total biomass}) = \ln(a_0 + a_1\text{DBH}) + \in.$$

Through this transformation, the error variance became constant but it was not any more in linear form as the dependent variable total biomass became nonlinearly dependent on the coefficients a_0 and a_1. So in this case,

Table 2. Results of fitting the model: ln (total biomass) = ln(a_0) + $a_1$ln (dbh) + $\in$

Locations	Intercept	Log (DBH)	R^2	EMS	n
Guna	10.59 (0.17)	2.41 (0.07)	0.957	0.0489	63
Vidisha	11.41 (0.06)	2.59 (0.03)	0.981	0.0417	235
Tikamgarh	11.52 (0.12)	2.91 (0.08)	0.874	0.0839	51
Chhattarpur	11.74 (0.18)	2.80 (0.07)	0.961	0.131	69
General	11.39 (0.06)	2.64 (0.03)	0.964	0.0930	418

Standard errors in parenthesis.

Table 3. Results of fitting the model: ln (total biomass) = ln(a_0) + $a_1$ln (dbh × height) + $\in$

Locations	Intercept	Log (DBH × height)	R^2	EMS	n
Guna	6.344 (0.037)	1.619 (0.030)	0.979	0.0211	63
Vidisha	6.132 (0.008)	1.593 (0.010)	0.990	0.0166	235
Tikamgarh	6.434 (0.019)	1.473 (0.016)	0.893	0.0166	51
Chhattarpur	6.136 (0.026)	1.513 (0.018)	0.989	0.0327	69
General	6.190 (0.009)	1.557 (0.008)	0.988	0.0308	418

Standard errors in parenthesis.

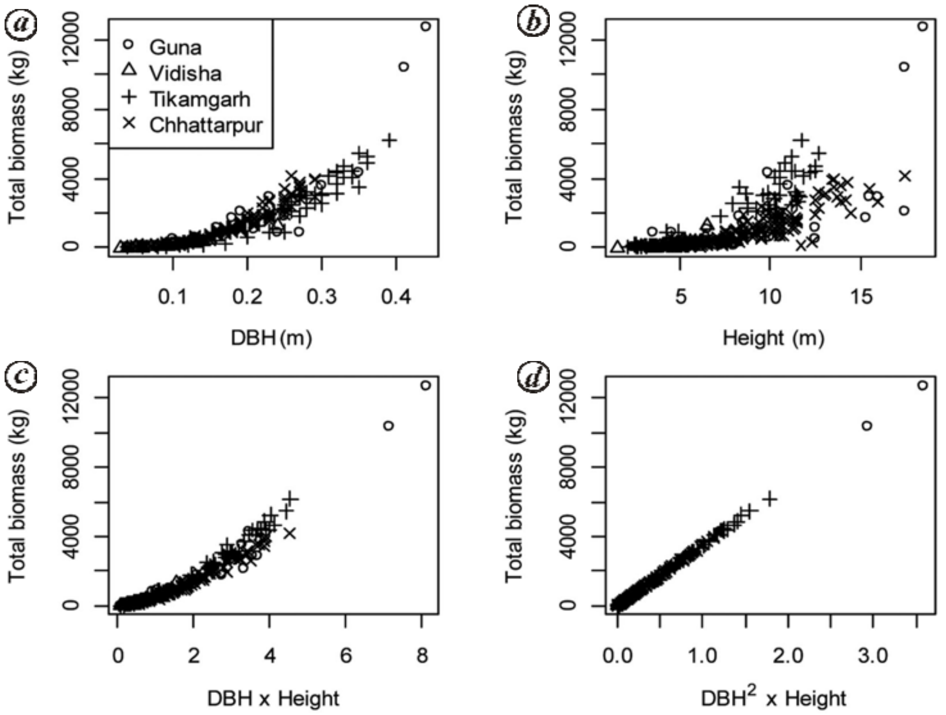

Figure 5. District-wise relationship between total biomass and DBH (***a***), height (***b***), DBH × height (***c***) and DBH^2 × height (***d***).

nonlinear modelling technique had to be followed. The other models tried here using different predictive variables were

Total biomass = $a_0\text{dbh}^{a_1} + \in$

Total biomass = $a_0(\text{height})^{a_1} + \in$

Total biomass = $a_0(\text{dbh} \times \text{height})^{a_1} + \in$

Total biomass = $a_0(\text{dbh}^2 \times \text{height})^{a_1} + \in$.

Again it was found that the greater the tree biomass, the greater will be the variability of the biomass, so log transformation of the data was performed before the models were tried. The models were fitted using ordinary least-square regression analysis and validation of these models was tested using several residual diagnostics.

Table 1 gives the descriptive statistics of the sample trees collected from 4 districts. Across the four sites the tree biomass ranged from 12.79 kg/tree to as high as 12707.92 kg/tree. When individual districts are considered,

Table 4. Results of fitting model: ln (total biomass) = ln(a_0) + $a_1$ln (height) + ∈

Locations	Intercept	Log (height)	R^2	EMS	*n*
Guna	0.220 (0.421)	3.092 (0.293)	0.645	0.361	63
Vidisha	–0.834 (0.20)	3.406 (0.099)	0.834	0.297	235
Tikamgarh	1.888 (0.253)	2.643 (0.123)	0.803	0.251	51
Chhattarpur	0.460 (0.241)	2.740 (0.138)	0.854	0.469	69
General	0.242 (0.137)	2.970 (0.072)	0.802	0.506	418

Standard errors in parenthesis.

Table 5. Results of fitting the model: ln (total biomass) = ln(a_0) + $a_1$ln (dbh^2 × height) + ∈

Locations	Intercept	Log (DBH^2 × height)	R^2	EMS	*n*
Guna	8.141 (0.040)	0.992 (0.010)	0.972	0.0074	63
Vidisha	8.168 (0.007)	0.999 (0.003)	0.977	0.0037	235
Tikamgarh	8.159 (0.007)	0.992 (0.003)	0.888	0.0018	51
Chhattarpur	8.161 (0.021)	1.00 (0.005)	0.978	0.0070	69
General	8.165 (0.006)	0.999 (0.002)	0.988	0.0046	418

Standard errors in parenthesis.

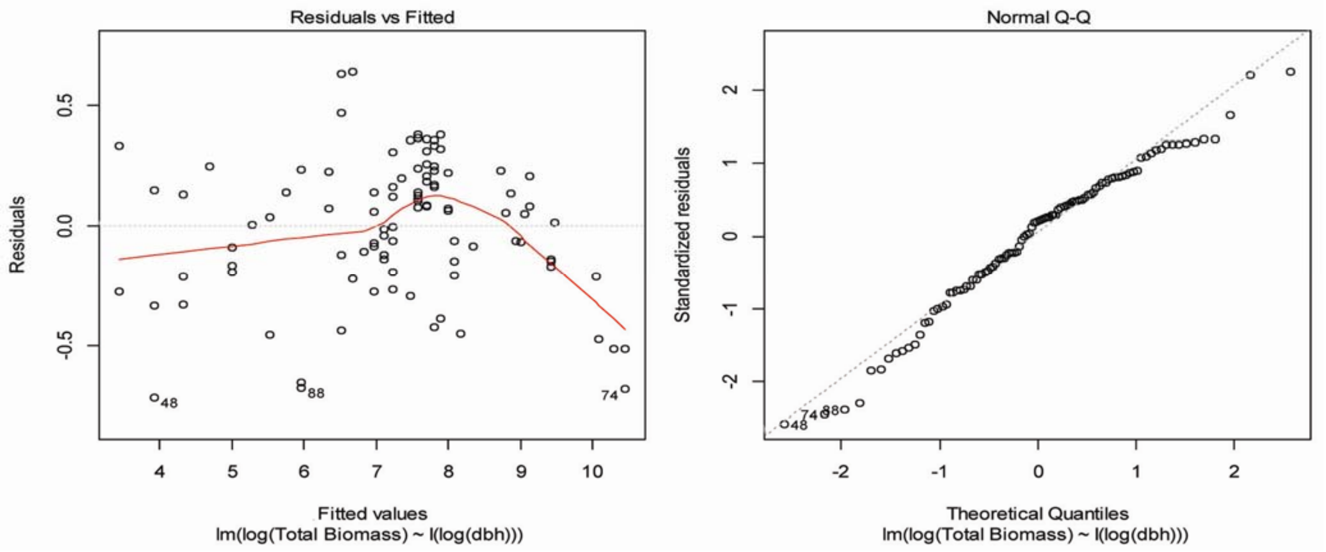

Figure 6. Residuals plotted against the fitted values (left) and quantile-quantile plot (right) of the residuals obtained from the linear model.

the highest variance per tree total biomass production was found in Chhattarpur and the least variance was found in Guna. The SW value in Table 1 represents the results of Shapiro-Wilk test[17] for normality, which in most of the cases indicate deviation from normality of the given variable and requires transformation for their further analysis. The relationship between tree height and dbh varied depending on the sites ($P < 0.01$) as the young teak trees dominated areas had lower heights than the mature ones at a same dbh (Figure 4). For different combinations like dbh (Figure 5 *a*) and dbh × height (Figure 5 *c*), they accounted for 87–98% and 89–98% variations respectively (Tables 2 and 3). Tree height was found to be the worst parameter to explain the variation of total biomass (Figure 5 *b*) accounting for 64–85% variation (Table 4). It has been observed that dbh^2 × height was strongly correlated with calculated total biomass (Figure 5 *d*) and in every district the dbh^2 × height was highly associated with total biomass accounting for 89–99% variation (Table 5). So, as the allometric relationship taking dbh^2 × height as the effect variable was found to be most suitable, it was essential to perform residual diagnostics to confirm that the assumptions of regression are satisfied (Figure 6). Even though there is a hint of slight structure in the residual versus fitted values, it may be considered that the errors of the fitted model are normal with constant variance.

This type of generalized equations developed here are of much use specially for estimating forest resources and thereby estimating regional carbon sequestration. It was found that only dbh^2 × height was the most stable and also the best predictor of tree biomass in case of all the four districts and the simple allometric equation developed using this predictor can give a robust estimate of the total biomass production of teak grown in this area without any kind of site-specific relationships.

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Received 27 June 2015; revised accepted 1 October 2015

doi: 10.18520/cs/v110/i3/414-419

Evidence of wildfires in the Late Permian (Changsinghian) Zewan Formation of Kashmir, India

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The first record of palaeo-wildfire evidence in the form of charcoal is documented from the Late Permian Zewan Formation of the Kashmir region, northwest Himalaya. This evidence is in the form of fragments of tracheids that show homogenized cell walls, a characteristic feature of charcoal. Considering that palaeo-wildfire studies provide important palaeoecological information, the present study is significant, as it allows reconstructing new information about environmental conditions during the deposition of the sediments of the Late Permian Zewan Formation.

Keywords: Charcoal, Gondwana, Himalayan region, Late Palaeozoic, marine environment.

THE Tethyan realm has been globally accepted as a hub for geoscientific studies, and Kashmir – a part of north west Himalayan region, in particular, has been considerably explored for its wealth of data on various geoscientific aspects including stratigraphy, geochemistry and palaeontology of its Carboniferous, Permian and Triassic sediments[1]. However, palaeo-wildfire studies have so far never been carried out for this area.

Although numerous Late Palaeozoic palaeo-wildfire studies have been carried out in the Northern Hemisphere (e.g. Europe, North America and China), those from Gondwana areas are not that common[2,3]. Despite the first description of charcoal made by Glasspool[4] from the Permian of Australia, macroscopic charcoal evidences have been recorded from Brazil, South Africa, India[3] and Antarctica[5] only recently.

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