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ORIGINAL ARTICLE

Assessment of inherent vulnerability of forests at landscape level: a case study from Western Ghats in India

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Abstract Assessment of vulnerability is an important step in building long-term resilience in the forestry sector. The objective of this paper is to present a methodological approach to assess inherent vulnerability of forests at landscape level. The approach involves use of vulnerability indicators, the pairwise comparison method, and geographic information system (GIS) tools. We apply this approach to assess the inherent vulnerability of forests of the Western Ghats Karnataka (WGK) landscape, which is a part of the Western Ghats biodiversity hotspot in India. Four vulnerability indicators, namely biological richness, disturbance index, canopy cover, and slope, are selected. We find that forests in 30, 36, 19, and 15 % grid points in this region show low, medium, high, and very high inherent vulnerability, respectively. The forest showing high and very high inherent vulnerability are mostly dry deciduous forests and plantations located largely on the eastern side of the landscape. We also find that canopy cover is one of the key indicators that determine the inherent vulnerability of forests, and natural

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forests are inherently less vulnerable than man-made plantations. Spatial assessment of inherent vulnerability of forests at landscape level is particularly useful for developing strategies to build resilience to current stressors and climate change in future.

Keywords Forest · Indicators · Inherent vulnerability · Plantation · Resilience · Vulnerability assessment

1 Introduction

Forests are a vital global resource with large implications for global biodiversity (Myers et al. 2000), distribution of fresh water (Ellison et al. 2012), and carbon cycle. However, during the twenty-first century, forest ecosystems could become vulnerable to climate and non-climate stressors (IPCC 2014). Exposure and vulnerability are key determinants of such risk and reducing vulnerability and increasing resilience are important risk management approaches (IPCC 2012). To deal with the risks to forests, assessment of vulnerability to identify the drivers of vulnerability is a critical pre-requisite (Murthy et al. 2011; Ribot 2011).

The concept of vulnerability and its assessment can be operationalized either prior to (starting-point approach) or after (end-point approach) the occurrence of a hazard. The starting-point approach to assess vulnerability considers vulnerability to be “something that exists within systems independently of external hazards” (Brooks 2003, p. 4). Brooks (2003, p. 4) further argues that “for vulnerability arising purely from the inherent properties of non-human systems or systems for which the term ‘social’ is not appropriate the term ‘inherent vulnerability’ might be used.” Forest ecosystems are biophysical systems and are characterized by a host of compositional (e.g., species diversity), structural (e.g., canopy cover density), and process-based (e.g., photosynthesis) inherent properties. These inherent properties make an undisturbed forest resilient. Conversely, in case of a disturbed forest, these properties are degraded and determine the propensity of forest to suffer adverse effects. Inherent vulnerability thus represents the extent by which the compositional and structural attributes and functionality of a forest are degraded as compared to undisturbed forests. It further provides a measure for lack of current potential to counter and prevent harm in future. Application of the concept of inherent vulnerability is useful to understand the factors that enhance such propensity of a forest ecosystem (Sharma et al. 2015). In our opinion, the manageability of forest ecosystems in anticipation of climate change begins with the assessment of inherent vulnerability and improves by addressing the current sources of vulnerability.

Vulnerability assessment studies exclusively for forests at landscape level are lacking; the available studies combine forestry sector along with several other sectors at landscape level (Wang et al. 2008) or regional scale (Lindner et al. 2010; Metzger et al. 2006). In this study, we develop a tool to assess inherent vulnerability of forests for risk management under current climate. The choice of assessment at landscape level is guided by the understanding that to preserve forests, the whole landscape should be considered as a conservation unit (Niemelä 1999; Haila and Kouki 1994). In the present study, landscape is understood as an area composed of adjacent and interacting ecosystems that are related because of geology, landforms, soils, climate, biota, and human influences. Furthermore, landscape level in forestry planning and practices stands for “the appropriate spatial or temporal scale for planning, analysis, and improvement of management activities to achieve ecosystem management objectives” (Price 2008). The following are the specific objectives of the study.

(a) To develop a methodological approach to assess inherent vulnerability of forests at landscape level.
(b) To apply the methodological approach for assessment of the inherent vulnerability of forests in Western Ghats Karnataka (WGK) landscape.

1.1 The Western Ghats Karnataka landscape

WGK landscape is a global biodiversity hotspot (Myers et al. 2000) located along the western coast in peninsular India and is spread across six states. This 1500-km-long (between 8° N and 21° N latitude) and 48 km (minimum) to 210 km (maximum) wide (between 72° E and 78° E longitude) landscape meets the water needs of about 245 million people (GOI 2011). The topographical heterogeneity in the WG landscape is highlighted by the altitudinal variation from sea level to about 2675 m above sea level. Humid and tropical climate dominates the landscape and the main soil types found are red, lateritic, black, and humid soils (Subramanyam and Nayar 1974). About 60 % of WGK landscape falls in Karnataka state (WGK landscape), which constitutes the vulnerability assessment area for the present case study. Of the 38 natural heritage sites identified by the United Nations Educational, Scientific and Cultural Organization (UNESCO) 10 sites are in WGK landscape in Karnataka state. The WGK landscape is characterized by high species endemicity, high rainfall gradient (7500 to 600 mm per year across the landscape from west to east), distinct 6-month-long wet season (June–November), altitudinal variation of about 1100 m, designated wildlife protected areas (WPA) spreading over 15 % of the forest area, and a human population density of <100 person/km^2 in forest dominated areas (GOI 2011).

1.2 Delineating the boundary of the WGK landscape

WGK landscape spreads between 11° and 16° N latitude and 74° and 77° E longitude. The boundary of the WGK landscape was obtained in geographic information system (GIS) format from the Karnataka Forest Department (KFD). Identification and delineation of WGK landscape by KFD is based on considerations of geological features, contiguity of forests, socio-cultural perception by the communities, and identification of Western Ghats area for implementation of government schemes in the past. The total area of the landscape is 4.479 Mha of which 2.609 Mha (58 %) is under forest cover.

1.3 The forest types in WGK landscape

Four major tropical forest types, namely wet evergreen (EG), semi-evergreen (SEG), moist deciduous (MD) and dry deciduous (DD) forests, and man-made plantations (PL), are found in WGK landscape. The wet evergreen forests have multiple canopy layers with species such as *Dipeterocarpus alatus*, *Vateria indica*, *Canarium strictum*, and *Mesua ferrea* in the top canopy; *Albizzia odoratissima* and *Artocarpus lakoocha* in the middle canopy; and *Limonica acidissima* and *Vitex negundo* in the understory. Placed between wet evergreen and moist deciduous, the semi-evergreen forests host evergreen as well as deciduous forest species. The common species found in these forests are *Dipterocarpus indicus* and *Hopea parviflora*. In the moist deciduous forests, the species remain deciduous only for a short time during March and April. The prominent species found in these forests include *Dalbergia latifolia*, *Tectona grandis*, *Terminalia paniculata*, and *Anogeises latifolia*. The undergrowth in these forests consists of bamboo in open patches and canes on wet ground. The dry deciduous forests in the Western Ghats are located on the eastern side in the rain shadow region and host species such as *Terminalia tomentosa*, *Lagerstromia lanceolata*, *Phyllanthus emblica*, and *Cassia fistula*. In the plantation forests, Teak (*Tectona grandis*), Acacia (*Acacia auriculiformis*, *Acacia hybrid*, etc), Eucalyptus (*Eucalyptus grandis*, *Eucalyptus citriodora*, etc), Casuariana (*Casuariana equisetifolia*), and Silver Oak (*Greviliea robusta*) species are found.

2 Methods and materials

The conceptual framework to understand and assess the inherent vulnerability of forests in the context of WGK landscape is presented in Fig. 1. The purpose of assessing the inherent vulnerability of forests of the WGK landscape is to conserve the forests and the forest ecosystem services in the long term.

The following steps are used in the assessment.

Step 1: Stratification of the forests in the landscape

Forests within WGK landscape differ in terms of forest-type, status of biodiversity, and the extent of disturbance, and thus their inherent vulnerability is expected to be different. The assessment and analysis of inherent vulnerability in the present study is carried out for different forest types and for two canopy cover density classes (open forests having <40 % and dense forests having >40 % canopy cover density).

Step 2: Selection of indicators

The framework for selection of vulnerability indicators for WGK landscape is presented in Fig. 2. The choice of vulnerability indicators is narrowed down by invoking expert judgment to quantifiable variables pertaining to biodiversity, physical structure of forests, and the factors of disturbance. The purpose of the

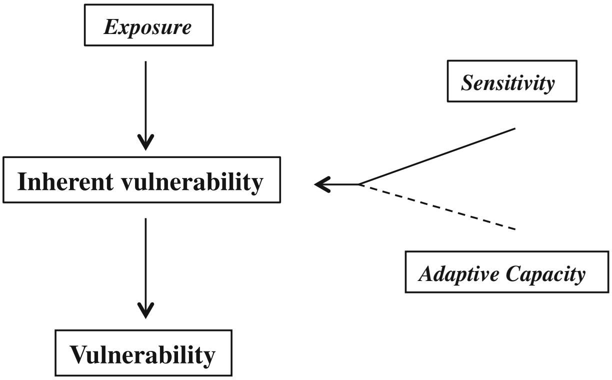

Fig. 1 Conceptual model adopted for assessing the inherent vulnerability of forests in the Western Ghats Karnataka (WGK) landscape. Sensitivity and adaptive capacity are internal properties of a system and determine the inherent vulnerability. Inherent vulnerability of a system is directly proportional to sensitivity and inversely proportional to adaptive capacity. *Dashed line* indicates reduction in inherent vulnerability owing to adaptive capacity of a system. A system with lower inherent vulnerability is likely to be more resilient

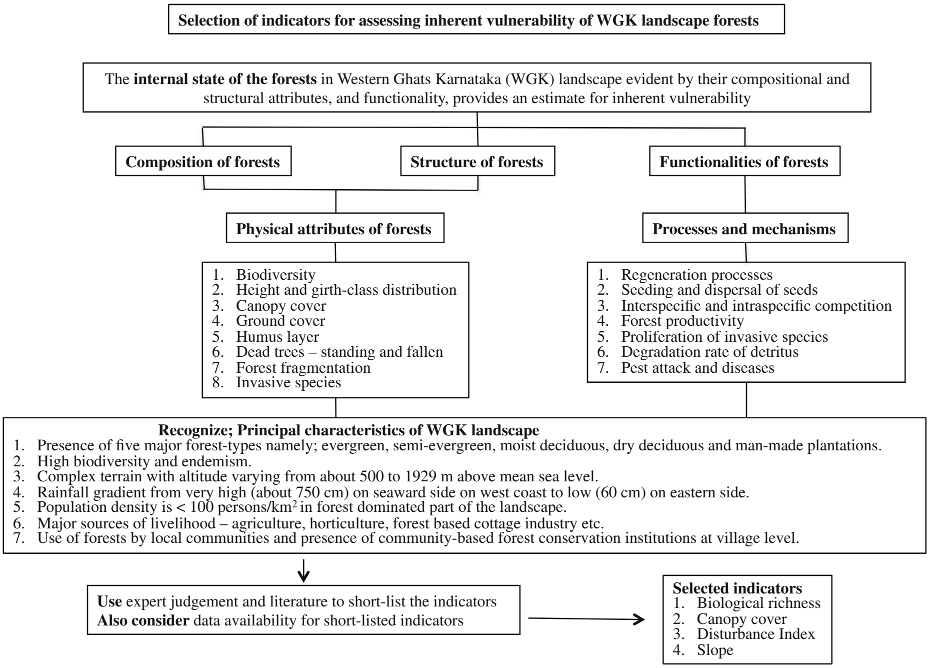

Fig. 2 Framework for identification of indicators for assessment of inherent vulnerability of forests at landscape level. Inherent vulnerability of a forest system is estimated by assessment of its internal state, which is determined by the composition and structure of a forest and the status of ecological processes. The framework combines information about forests and the factors influencing forests in the landscape and employs expert judgment to identify the indicators

assessment, the principal characteristics of the landscape pertaining to climate, geology, forest types, anthropogenic pressures on forests, forest management, and the constraints with respect to availability of data on the indicators are considered in the expert judgment. Often, the lack of data becomes the deciding factor in selection of vulnerability indicators. Four vulnerability indicators, namely biological richness, canopy cover, disturbance index, and slope, are identified for assessment.

Step 3: Indicator weights

To develop weights for the indicators, pairwise comparison method (PCM) was used (Wang et al. 2008). Ten experts and researchers independently assigned weights using PCM technique (Saaty 2008). Arithmetic mean of indicators weights assigned by the experts and researchers was calculated and adopted. The weights assigned to the indicators are presented in Section 4.

Step 4: Placing the landscape onto a regular grid

The boundary of the landscape is marked and the landscape area is divided into area grids of $2.5' \times 2.5'$ size (approximately 18.66 km^2). There are 2400 grid points in the landscape. The forest types map for the landscape was obtained from the Karnataka Forest Department. Using GIS technique, the landscape area was stratified into five strata, namely wet evergreen forests (EG), semi-evergreen forests (SEG), moist deciduous forests (MD), dry deciduous forests (DD), and man-made forestry plantations (PL).

Step 5: Classification of forest grid points under a particular forest-type

A grid point having forest area (area with >10 % tree canopy cover) is classified as forest-grid. Out of a total number of 2400 grid points in the WGK landscape, 2372 are forest grid points, and the remaining 28 are non-forest points. A forest grid point is classified under a forest-type that constitutes majority of the forest area.

Step 6: Estimation of vulnerability value at a grid point

The details of the indicator values and their categorization in different vulnerability classes, the sources of data, and the measured variables are provided in Table 1. The range of estimated value for an indicator is first clustered into low, medium, and high vulnerability classes. For example, the value of biological richness (BR) obtained from the database of Indian Institute of Remote Sensing (IIRS) varies between 2 and 91 with biological richness increasing from 2 to 91. This dataset classifies BR values into four classes namely low (2–33), medium (34–49), high (50–69), and very high (70–91) BR. In the present study, we have considered only three BR classes by merging high and very high BR classes into one class and termed it as high BR class (50–91). As vulnerability varies inversely with the BR, the vulnerability class values of 1 (low), 2 (medium), and 3 (high) are assigned for BR range values of 50–91, 34–49, and 2–33, respectively. The vulnerability value (*VV*) for a grid point is obtained in three

Table 1 Details on the indicators selected for assessment of inherent vulnerability of Western Ghats Karnataka (WGK) landscape forests

Indicator values and vulnerability classes for the WGK landscape

Indicator	Range of indicator value (vulnerability class) (indicator measure value assigned)	Source of indicator values	Indicator measurable
Biological richness	Biodiversity richness value a. 50–91 (low) (1) b. 34–49 (medium) (2) c. 2–33 (high) (3)	Indian Institute of Remote Sensing (IIRS) data set available as part of Biodiversity Information System (BIS) at www.bis.iirs.gov.in.	Area-weighted average biodiversity richness value
Disturbance Index	Disturbance Index value a. <18 (low) (1) b. 19–23 (medium) (2) c. 24–72 (high) (3)	As above	Area-weighted average Disturbance Index value
Canopy cover	Canopy cover percentage a. >70 (low) (1) b. 40–70 (medium) (2) c. 10–40 (high) (3)	Forest Survey of India (FSI) data set on forest canopy cover	Area-weighted average cover density
Slope	Ground slope in degree a. <5 (low) (1) b. 5–15 (medium) (2) c. >15 (high) (3)	Georeferrenced contour layer obtained from Karnataka Forest Department (KFD)	Area-weighted average slope using 50 m interval contours

The indicator data sources are the national level data bases generated by the agencies of the government in India. High indicator values for biological richness and canopy cover indicate low vulnerability, while high indicator values for disturbance index and slope indicate high vulnerability. Value of an indicator at a grid point is calculated as the area-weighted average for an indicator obtained by using the indicator values for all the pixels falling within that grid point steps. In the first step, area-weighted vulnerability-class value (*VCV*) for an indicator for a grid point is obtained as sum of the products of the proportion of forest area under different vulnerability classes and the corresponding vulnerability-class values (3-high, 2-medium, and 1-low vulnerability). In the second step, *VCV* is multiplied by weight (W_i) to obtain vulnerability due to an indicator. Finally, the vulnerability value at a grid point (VV_j) is obtained by adding the vulnerability values for all the indicators.

Step 1: $VCH_{ij}=(P_{ij1}\times 1+P_{ij2}\times 2+P_{ij3}\times 3)$
Step 2: $VV_{ij}=(VCV_{ij}\times W_i)$
Step 3: $VV_j=\sum_{i=1}^{4}\left(VV_{ij}\right)$

VCV_{ij} is the vulnerability class value for *i*th indicator in *j*th grid point; P_{ij1}, P_{ij2}, and P_{ij3} are the proportions of the area of a grid point under vulnerability classes 1, 2, and 3 for *i*th indicator in *j*th grid point; W_i is weight for *i*th indicator; VV_{ij} is vulnerability value for *i*th indicator in *j*th grid point; VV_j is vulnerability value for *j*th grid point.

Step 7: Developing inherent vulnerability profile

To develop the spatial profile of inherent vulnerability, the vulnerability values for forest grid points are subjected to cluster analysis inbuilt in the Arch GIS 10 software. Four vulnerability classes namely low, medium, high, and very high vulnerability are identified. The profile of inherent vulnerability is presented in Fig. 3.

3 Summary description of indicators

Four indicators, namely biological richness, disturbance index, canopy cover, and slope, are selected to assess the inherent vulnerability of the forests of WGK landscape.

3.1 Biological richness

The dataset for biological richness (and disturbance index) indicator is obtained from the Indian Institute of Remote Sensing (IIRS), a Government of India agency. This dataset hosted by IIRS is part of Biodiversity Information System (BIS) available at www.bis.iirs.gov.in. The biological richness (BR) indicator is a composite of five parameters, namely species richness (SR), ecosystem uniqueness (EQ), terrain complexity (TC), biodiversity value (BV), and disturbance index (DI) (Roy et al. 2012). BR takes into account factors of ecology, geology, economic value, usefulness to stakeholders, and disturbances and indicates the present status of the species diversity as well as the habitats. It provides a measure of potential for hosting biodiversity (Roy et al. 2012). Therefore, by using the information about BR, it is the loss in potential of a habitat to be biologically richer that is estimated to assess inherent vulnerability. Thus, in this study, a lower value of BR is considered to represent lower adaptive capacity of forests or conversely higher vulnerability. Accordingly, the following vulnerability classes have been identified for different BR value classes in the WGK landscape: low vulnerability (BR value 50–91), medium vulnerability (BR value 34–49), and high vulnerability (BR value 2–33) (Table 1).

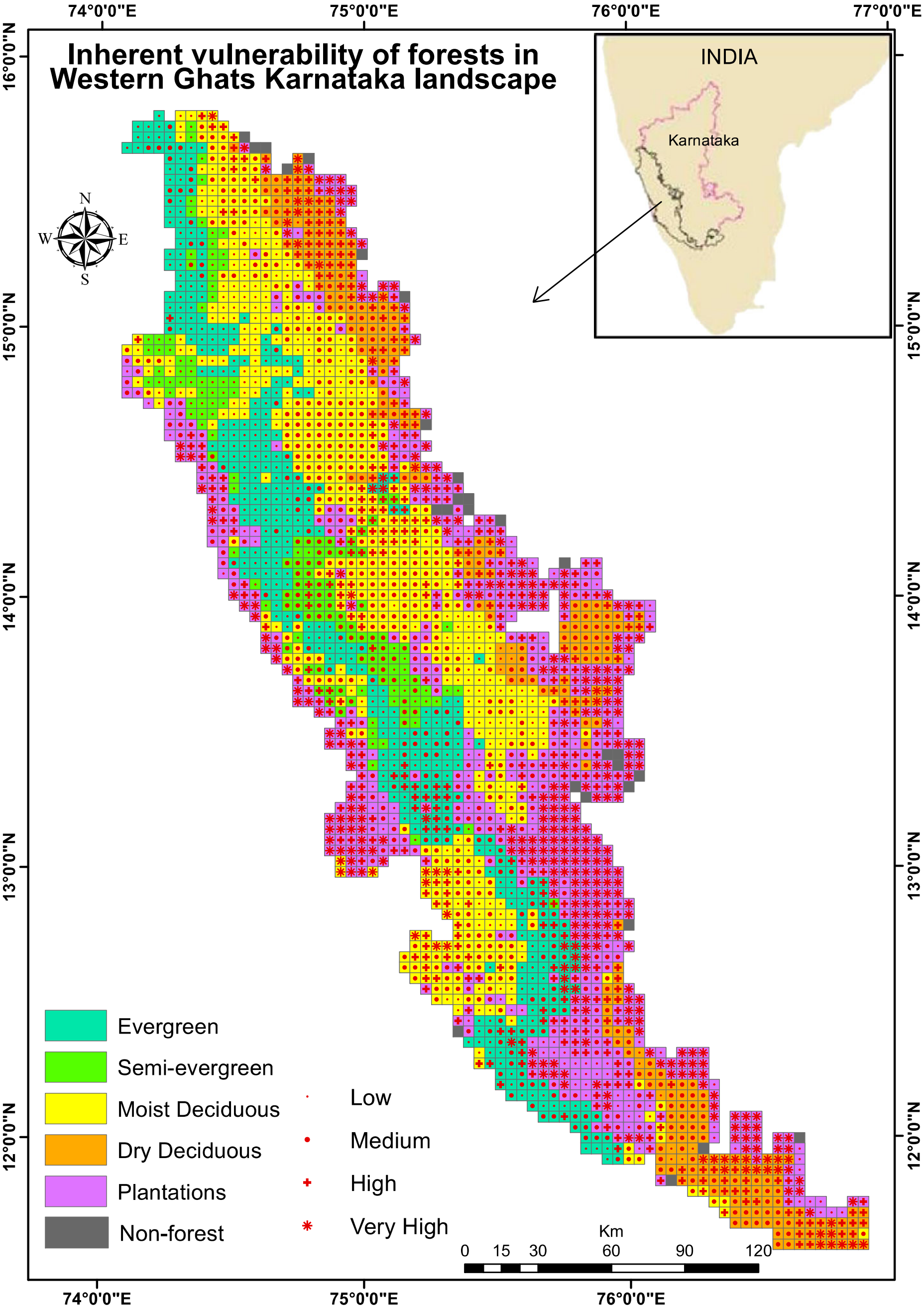

Fig. 3 Distribution of inherent vulnerability in Western Ghats Karnataka (WGK) landscape according to forest types. Inherent vulnerability in the landscape is shown in low, medium, high, and very high vulnerability classes. Generally, forest grid points with high and very high inherent vulnerability are located in plantation forests, and in the dry deciduous forests on the eastern side in the landscape

3.2 Disturbance index

The spatial dataset for DI is also part of Biodiversity Information System (BIS) dataset. DI is composed of five variables, namely fragmentation (F), porosity (P), interspersion (I), juxtaposition (J), and biotic disturbance (BD) (Roy et al. 2012). DI combines the current spatial structure of forests and ground-based disturbance indicators such as status of invasion, regeneration, and low girth class (Roy et al. 2012). Furthermore, DI is one of the five components of BR. DI is included as part of BR to account for the “level of stress on the biologically rich areas” (Roy et al. 2012). However, the implications of DI for forest vulnerability are more and arise from the compromised status of the resilience building attributes of forests such as complex forest structure and forest contiguity. DI represents these forest attributes through porosity, interspersion, juxtaposition, and forest fragmentation. Since BR and DI account for different aspects of vulnerability—BR accounts for vulnerability due to loss of species richness and the potential of a habitat, and DI accounts for the change in the spatial structural elements and fragmentation of forests—DI is also selected as an independent indicator. The IIRS data computes the DI values in the range 0–72 and classifies in four classes, namely very high (29–72), high (24–28), medium (19–23), and low (<18) disturbance (Roy et al. 2012). In the present study, the high and very high DI classes have been merged and three classes indicating low (DI value: <18), medium (DI value: 19–23), and high (DI value: 24–72) vulnerability are used as vulnerability increases with disturbance (Table 1).

3.3 Canopy cover

The canopy cover indicator provides a measure for forest area covered by tree canopy, which determines the microclimate under a forest. Kauffman and Uhl (1990) have reported that a 50 % reduction in canopy cover in Amazonian forests increased average temperature by 10 °C and decreased relative humidity by 35 %. Thinning of canopy cover can therefore drastically alter the conditions of light, temperature, moisture, and wind in a forest and thereby can have severe implications for forest resilience. These changes can potentially mediate or trigger other changes in a forest ecosystem such as increased inter-species competition. Thinning of canopy cover is therefore an important indicator of forest vulnerability.

The spatial data on canopy cover was obtained from Forest Survey of India (FSI), a Government of India agency. The three canopy cover classes (open, moderately dense, and very dense forests correspond to 10–40, 40–70, and >70 % canopy density, respectively) used by the FSI for reporting the status and quality of forests have been adopted for categorizing canopy cover in different vulnerability classes. In the present study, the canopy cover classes with 10–40, 40–70, and >70 % canopy density have been identified with high, medium, and low vulnerability classes, respectively (Table 1).

3.4 Slope

Forests located on steep slopes are inherently more vulnerable from landslides and soil erosion than those located on gentle slopes. WGK landscape has undulating terrain that frequently rises and transforms into mountain-valley system with steep slopes. The steep slopes combined with heavy monsoon rainfall, network of roads, and anthropogenic pressure add to the vulnerability of forests. Furthermore, terrain complexity, a component of BR indicator, accounts for variability of terrain and thereby the habitat heterogeneity but not for the propensity of the habitat to erosive forces of water and wind. Slope is thus selected as a vulnerability indicator. The spatial pattern of slope at 50-m contour-interval was obtained from the Karnataka Forest Department. The slope classification values of <5, 5–15, and >15° indicating gentle, strong, and steep slope classes are used to represent low, medium, and high vulnerability (Wang et al. 2008; FSI 2002).

4 Results and discussion

The spatial data on forest types obtained from the Karnataka Forest Department shows the area under different forest types: evergreen—0.58 Mha, semi-evergreen—0.24 Mha, moist deciduous—0.76 Mha, dry deciduous—0.31 Mha, and plantations—0.72 Mha.

4.1 Distribution of the forest area

Break-up of forest area into forest types is presented in Table 2. Out of the 2372 forest grid points in the landscape, it is found that 64 % have more than 1000 ha (i.e., at least 53 % of the total geographical area is under tree canopy cover) and only 8 % forest grid points have <100 ha of the total geographical area under forest cover. There are no grid points that have <100 ha forest cover in case of semi-evergreen forests. For plantation forest, 18 % (138 out of 751) grid points have <100 ha under forest cover. Furthermore, 74 % (138 out of 187) grid points having forest area <100 ha are plantation grid points and in remaining 26 % natural forests are majority forest-type. Generally, the number of grid points having low forest cover (i.e. <100 ha of the area under forest cover) in case of natural forest is significantly less compared to plantation forests. Majority of the plantation forests are located in the eastern and western fringe of the landscape. These areas are under severe anthropogenic pressure.

All the 2372 forest grid points have been considered for assessment. Very few grid points (<5 %) have <50 ha forest area and 76 % of these have forest area between 10 and 50 ha. Considering all the forest grid points irrespective of the extent of forest area at a grid point is necessary because the purpose of assessment is to identify the forest grid points under different vulnerability classes.

Table 2 Forest grid points in different area classes according to forest types

Forest-types	Number of grids with forest area (ha)							
	<5	5–10	10–50	50–100	100–500	500–1000	1000–1500	>1500
Evergreen	2	2	4	5	15	28	168	232
Semi evergreen	0	0	0	0	4	41	74	40
Moist deciduous	3	0	2	8	48	85	233	298
Dry deciduous	2	0	11	10	72	80	64	90
Plantations	8	11	72	47	170	122	227	94
Total	15	13	89	70	309	356	766	754

Majority of the low forest cover (<100 ha) grid points are contributed by man-made plantation forests. Natural forest grid points have higher proportion of area under forest cover

4.2 "Open" versus "dense" canopy forests in the landscape

Factors such as soil depth, moisture regime, and climate in WGK landscape are favorable to high vegetative productivity and dense forest canopy. However, over a period of time, human activities in the landscape such as cultivation of cash crops (e.g., coffee), expansion of agriculture, housing and road network, forest biomass harvesting, cattle grazing, forest fire, and mining activities have had adverse implications for forest canopy cover. In the present study, forests having <40 % canopy cover density have been considered as open forests (FSI 2011). Such forests are characterized by high disturbance, low stocking, and higher abundance of invasive species, and as a consequence are likely to have lower resilience and higher inherent vulnerability. Forests with >40 % canopy cover density have been considered as dense forests. Of the 2372 forest grid points, 702 (30 %) have average canopy cover of less than 40 % and 1670 (70 %) have average canopy cover of more than 40 % (Table 3) in the landscape. Considering forest types, it is observed that evergreen forest grid points have least percentage (7 %) with <40 % canopy cover followed by semi-evergreen (9 %), moist deciduous (23 %), dry deciduous (40 %), and plantations (48 %).

4.3 The vulnerability indicators and indicator weights

Inherent vulnerability has been assessed by aggregating four vulnerability indicators, namely biological richness (BR), disturbance index (DI), canopy cover (CC), and slope (S). The weights for the indicators are BR-0.552, DI-0.266, CC-0.123, and S-0.059.

4.4 Segregating forest grid points in different inherent vulnerability classes

The vulnerability values for forest grid points in the landscape are estimated between 1.06 and 2.90. This range of grid point vulnerability values are segregated under four cluster-groups using Jenks natural breaks classification method, which defines data clusters by minimizing variance within a cluster and maximizing it between clusters. Accordingly, the forest grid

Table 3 Number and percentage of forest grid points having open (<40 % density) and dense (>40 % density) canopy cover according to forest types

Forest-types	Forest area (ha)	Total grids		Grids with <40 % canopy cover		Grids with >40 % canopy cover	
		Number	Percent	Number	Percent	Number	Percent
Evergreen	584,500	456	19.22	32	7.02	424	92.98
Semi evergreen	240,200	159	6.70	15	9.43	144	90.57
Moist deciduous	760,200	677	28.54	158	23.34	519	76.66
Dry deciduous	306,300	329	13.87	133	40.43	196	59.57
Plantations	718,000	751	31.66	364	48.47	387	51.53
Total	2,609,200	2372		702		1670	
Non-Forest	30,800	28					

Approximately 68 and 32 % grid points have natural and plantation forests, respectively. Compared to plantations, natural forests have higher percentage of grid points under dense canopy cover points are clustered under low (1.06–1.44), medium (1.44–1.87), high (1.87–2.40), and very high (2.40–2.90) inherent vulnerability classes.

4.5 Profile of inherent vulnerability in the landscape

Out of the 2372 forest grid points in the landscape, 30, 36, 19, and 15 % grid points are assessed in low, medium, high, and very high inherent vulnerability classes, respectively. The spatial distribution of inherent vulnerability in the landscape is shown spatially in Fig. 3. Generally, high and very high vulnerability grid points are located toward the fringes of the landscape in dry deciduous forests and plantations. While for evergreen, semi-evergreen, and moist deciduous forests, the percentage of grids with high and very high inherent vulnerability is less than 14 %; in the case of dry deciduous forests and plantations, this percentage is 47 and 65 %, respectively (Table 4). The grid points having higher inherent vulnerability are located mainly on the eastern side of the landscape, which predominantly hosts dry deciduous forests and plantations. The higher inherent vulnerability of dry deciduous forests and plantations could be attributed to the following reasons. (1) Because of the more gentle terrain on the eastern side the forests are more accessible and have higher anthropogenic pressure. (2) The forests on eastern side have lower productivity because of less rainfall. (3) In the dry deciduous belt, plantations have been raised because such forests could not regenerate due to unrelenting anthropogenic pressure and these areas were in various stages of degradation. The results suggest that plantation forests are more vulnerable than natural forests in the WGK landscape (Thompson et al. 2009).

Among the natural forest types, semi-evergreen forests are least vulnerable as no semi-evergreen forest grid point is assessed in very high inherent vulnerability class and the total percentage of grid points with high and very high inherent vulnerability for this forest-type is the lowest (11 %) (Table 4). The evergreen forest-type has a total of 12 % grid points under high and very high inherent vulnerability classes. Under evergreen and semi-evergreen forest types, 88 and 89 % grid points, respectively, are under (combined) low and medium inherent vulnerability classes. The moist deciduous forests are placed in between evergreen and semi-evergreen on one side and dry deciduous and plantation forests on the other with 35, 51, 12, and 2 % of grid points in low, medium, high, and very high inherent vulnerability, respectively. Among natural forest-types, dry deciduous forests have highest inherent vulnerability in WGK landscape.

Table 4 Percentage of forest grid points in low, medium, high, and very high inherent vulnerability classes according to forest types. Plantation forests show higher inherent vulnerability than natural forest-types

Forest-type	Inherent vulnerability (percent grid points)			
	Very high	High	Medium	Low
Evergreen	2.85	8.99	25.44	62.72
Semi evergreen	0.00	10.69	35.85	53.46
Moist deciduous	1.92	11.82	51.26	35.01
Dry deciduous	10.64	36.78	48.63	3.95
Plantations	40.35	24.50	22.24	12.92

4.6 Forest degradation and inherent vulnerability

The ecological carrying capacity of the WGK landscape is sufficient to host dense canopy forests (GOI 2011) and any thinning of canopy cover to lower stocking is considered a sign of disturbance. Thus, forests with <40 % canopy cover have been considered as degraded forests. In this study, we consider forests having >40 % canopy cover density as resilient.

The distribution of high and very high inherent vulnerability grid points in open canopy and dense canopy cover categories shows that while 60 % forest grid points have high and very high inherent vulnerability in open forests, only 23 % dense forest grid points are under these classes. As against 9 % grid points in low inherent vulnerability class for open canopy forests, there are 39 % such grid points in dense canopy cover forests. This demonstrates that degraded forests with more open canopy cover have higher inherent vulnerability compared to those with denser canopy. Thus, it could be inferred that canopy cover is one of the most important contributing factors for the inherent vulnerability of forests in WGK landscape.

For evergreen, semi-evergreen, and moist deciduous forest-types, about 30 % grid points are in high and very high inherent vulnerability classes when the canopy is open. However, only about 10 % of the grid points show high and very high inherent vulnerability for these forest-types when the canopy cover is dense. The combined proportion of high and very high inherent vulnerability grid points, between open and dense canopy covers within a forest-type, is found to be 4:1 for semi-evergreen, 3:1 for moist deciduous, 2.7:1 for evergreen, 2.3:1 for dry deciduous, and 1.28:1 for plantations. This suggests that, with other factors remaining constant, the sensitivity of inherent vulnerability to canopy cover change is maximum in case of semi-evergreen forests and minimum for plantation forests. Compared to man-made plantation forests, the inherent vulnerability of natural forest-types is markedly more sensitive to canopy cover.

4.7 Inherent vulnerability and forest management

The term inherent vulnerability of forests relates to the loss in capacity of forests to resist or adapt to change. Such capacity depends on forest resilience, which is strongly tied to biodiversity (Thompson et al. 2009). Therefore, the factors that impact the status of biodiversity must be addressed to ensure resilience and adaptability of forests. Climate change is likely to bring additional stress to the forests of WGK landscape (Chaturvedi et al. 2011). Such additional climate stress may have implications for inherent vulnerability through exacerbated impacts of non-climate stressors. It is therefore useful to identify the current non-climate stressors and address them to secure resilience against future stressors including climate change. The present study in WGK landscape has addressed the following questions.

(a) What is the status and distribution of inherent vulnerability in WGK Landscape?
(b) How does inherent vulnerability in the landscape vary among forest-types?

Such information is useful for decision-making and has vital implications for forest management in the WGK landscape in following respects. First, it helps by identifying vulnerable forest areas of critical conservation importance such as wildlife corridors, special habitats, and areas of exceptional biological richness. Second, it prompts forest management to probe the site-specific sources of vulnerability and to design specific management response to address such vulnerabilities. Third, such information is necessary to justify the demand of forest management for resource allocation. Fourth, in the local socio-political context, such information could improve the understanding and connect of the leadership and stakeholders with the risks and thereby promote action for taking up adaptive forest management.

We have identified the location and canopy cover dependence of inherent vulnerability in the WGK landscape forests. Furthermore, because of their socioeconomic and ecological importance, all the remnant forests in this landscape should be conserved and networked to maintain the functionality of the landscape as one ecological unit. However, resource limitations necessitate prioritization of areas for management and hence areas having high and very high inherent vulnerability identified by the present study could provide guidance in this regard.

Our study also finds higher inherent vulnerability in dry deciduous and plantation forests located on the eastern side in the landscape. Participatory forest management involving local communities could be initiated and strengthened in such areas to deal with the vulnerability driven by anthropogenic pressure (Sharma et al. 2015). Community involvement would facilitate addressing the inherent vulnerability and thereby enhance forest adaptability under current climate as well as future climate. Such a process can also help in evolving a balanced policy approach with respect to development vis-à-vis forest conservation. For the forest areas of conservation importance (such as wildlife protected areas or those part of wildlife corridors) showing medium or higher inherent vulnerability, vulnerability assessments at local scale are required to identify the specific vulnerability source mechanisms to initiate appropriate vulnerability reduction actions. Periodic assessment of inherent vulnerability would help in identification of new factors that drive inherent vulnerability and could guide revision of forest restoration/adaptation plans (Füssel and Klein 2006; Sharma et al. 2013). Spatial distribution of inherent vulnerability in the landscape confirms the location-specific nature of vulnerability.

4.8 Applicability of assessment methodology

The approach adopted to understand and assess inherent vulnerability in the present study is consistent with that adopted in the latest assessment report of intergovernmental panel on climate change, which considers vulnerability according to starting-point approach in the risk assessment framework for decision-making (IPCC 2014). Assessment of inherent vulnerability is a precursor step, the outcome of which informs the process of developing management strategies for resource conservation. Thus to manage the risk to global forest resources, it is useful to assess inherent vulnerability and evolve informed management strategies for reducing it. Assessment of inherent vulnerability of forests gains importance as an insurance approach for long-term forest conservation under climate change (Sharma et al. 2013; Thompson et al. 2009). It is a “low or no regret” approach, as it would potentially yield net ecological and social benefits whether or not there is climate change.

To our knowledge, the present case study is the first attempt to assess inherent vulnerability of forests at landscape level. The case study involves a typical high-biodiversity high human-pressure tropical forest system. However, we believe that the methodological approach adopted in the case study has universal applicability in other climatic zones including sub-tropical and temperate zones.

5 Conclusions

Use of vulnerability indicators, pairwise comparison method (PCM), and GIS tools is a novel approach in forestry sector to assess inherent vulnerability at landscape level. Application of this methodological approach in the WGK landscape shows that 30, 36, 19, and 15 % forest grid points in the landscape have low, medium, high, and very high inherent vulnerability, respectively. Forests having high and very high inherent vulnerability are located largely toward the eastern boundary of the landscape in dry deciduous forests and plantations. Among the various forest-types found in the landscape, the inherent vulnerability varies in the following order: semi-evergreen<evergreen<moist deciduous<dry deciduous forests<plantation forests. We find that the biodiversity rich natural forests are less vulnerable than man-made plantation forests. Inherent vulnerability of forests is found to depend on canopy cover: forests with open canopy cover (<40 %) have higher inherent vulnerability compared to those with dense canopy cover (>40 %) in the landscape. The spatial profile of inherent vulnerability of forests in the WGK landscape shows that the forests in the central and southern part of the landscape have comparatively higher inherent vulnerability. The significance of inherent vulnerability assessment lies in its potential for reducing the risk under changing climate by addressing the current non-climate sources of vulnerability.

In conclusion, the present case study demonstrates the utility of our methodological approach, which is generic and can be applied to other forest landscapes by appropriate selection of vulnerability indicators and their weights. The methodology and the case study would add to the capacity of forest managers to assess the inherent vulnerability of forests at landscape level to address the risks under climate change.

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References

Brooks N (2003) Vulnerability, risk and adaptation: a conceptual framework. Tyndall Centre Working Paper 38

Chaturvedi RK, Ranjith G, Jayaraman M et al (2011) Impact of climate change on Indian forests: a dynamic vegetation modeling approach. Mitig Adapt Strateg Glob Chang 16:119–142

Ellison D, Futter MN, Bishop K (2012) On the forest-cover water yield debate: from demand- to supply-side thinking. Glob Chang Biol 18:806–820

FSI (2002) The manual of instructions for field inventory 2002. Forest Survey of India, Ministry of Environment and Forests, Government of India, Dehradun. http://www.fsi.nic.in/documents/manualforest_inventory_2.pdf. Cited 13 June 2014

FSI (2011) State of forest report 2011. Forest survey of India, Ministry of environment and forests, government of India, Dehradun. http://www.fsi.nic.in/cover_2011/chapter2.pdf. Cited 13 June 2014

Füssel H, Klein RJ (2006) Climate change vulnerability Assessments: an evolution of conceptual thinking. Clim Change 75:301–329

GOI (2011) Report of the Western Ghats ecology expert panel, ministry of environment and forests, government of India, New Delhi. www.moef.nic.in/downloads/public-information/wg-23052012.pdf. Cited 13 June 2014

Haila Y, Kouki J (1994) The phenomenon of biodiversity in conservation biology. Ann Zool Fenn 31:5–18

IPCC (2012) In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change. Cambridge University Press, Cambridge,
582 pp

IPCC (2014) Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1–32

Kauffman JB, Uhl C (1990) Interactions and consequences of deforestation and fire in the rainforests of the Amazon Basin. In: Goldhammer JG (ed) Fire in the tropical and sub-tropical biota. Springer, Berlin, pp 117–134

Lindner M, Maroschek M, Netherer S et al (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecol Manag 259:698–709

Metzger MJ, Rounsevell MDA, Acosts-Michlik L et al (2006) The vulnerability of ecosystem services to land use change. Agric Ecosyst Environ 114:69–85

Murthy IK, Tiwari R, Ravindranath NH (2011) Climate change and forests in India: adaptation opportunities and challenges. Mitig Adapt Strateg Glob Chang 16:161–175

Myers N, Mittermeier RA, Mittermeier CG et al (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858

Niemelä J (1999) Management in relation to disturbance in boreal forest. Forest Ecol Manag 115:127–134

Price DL (ed) (2008) Draft Michigan state forest management plan. Michigan department of natural resources, forest, mineral, and fire management division and wildlife division, Lansing. http://www.michigandnr.com/publications/pdfs/ForestsLandWater/ForestMgt/SFMPdraftApr2008.pdf. Cited 18 June 2013

Ribot J (2011) Vulnerability before adaption: towards transformative climate action. Glob Environ Chang 21: 1160–1162

Roy PS, Kushwaha SPS, Murthy MSR et al (2012) Biodiversity Characterisation at landscape level: National Assessment. Indian Institute of Remote Sensing, Dehradun, p 140. ISBN 81-901418-8-0

Saaty TL (2008) Decision making with the analytic hierarchy process. Int J Serv Sci 1(1):83–98

Sharma J, Chaturvedi RK, Bala G et al (2013) Challenges in vulnerability assessment of forests under climate change. Carbon Manage 4(4):403–411

Sharma J, Chaturvedi RK, Bala G et al (2015) Assessing ‘inherent vulnerability’ of forests: a methodological approach and a case study from Western Ghats, India. Mitig Adapt Strateg Glob Chang 20:573–590. doi:10.1007/s11027-013-9508-5

Subramanyam K, Nayar MP (1974) Vegetation and phytogeography of the Western Ghats. In: Mani MS (ed) Ecology and biogeography in India. Monographiae Biologicae, vol 23. Springer, Netherlands, pp 178–196

Thompson I, Mackey B, McNulty S et al (2009) Forest Resilience, Biodiversity, and Climate Change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems. Secretariat of the Convention on Biological Diversity, Montreal,
Technical Series no. 43, pp67

Wang XD, Zhong XH, Liu SZ et al (2008) Regional assessment of environmental vulnerability in Tibetan Plateau: development and application of a new method. J Arid Environ 72:1929–1939