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Impacts of disturbance on soil properties in a dry tropical forest in Southern India

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ABSTRACT

Grazing, fuelwood extraction and burning are common human activities in Indian forests. These activities can represent forest disturbances that drive the degradation of natural deciduous forest cover to scrub forest, with concurrent impacts on soils. The effects of human forest use on ecosystem functions were investigated in *Bandipur National Park (BNP)* in Peninsular India. This paper reports the impacts on surface soils. Soils were sampled from 200 locations covering four watersheds within the Park. These samples spanned a degradation gradient measured by a field disturbance index (FDI). Soil physical, nutrient and hydraulic properties were measured. Cation exchange capacity (CEC) and saturated hydraulic conductivity (K_s) were analyzed as key response variables describing nutrient availability and infiltration respectively. Effects of cattle and jeep trails on infiltration and bulk density were evaluated by sampling on-and-off trails. Trail density in research watersheds was estimated with satellite imagery. Soil nutrient availability is negatively impacted by disturbance, resulting from negative impacts on soil organic carbon (SOC) and clay content. Available water capacity (AWC) and saturated moisture content (SMC) were significantly higher in protected watersheds, attributed to reduced clay content in degraded watersheds. Off trails, high spatial variability in infiltration overwhelmed any meaningful trends with disturbance. However, infiltration was substantially reduced on trails as a result of significant increase in bulk density. The density of trails was considerably higher in degraded watersheds compared to protected watersheds. These results provide ground-based and remotely sensed evidence that forest disturbance within the Park has negative impacts on soil organic matter, nutrient availability and hydraulic characteristics. These have consequences for related ecological, nutrient cycling and hydrological processes, and the continuation of the services currently enjoyed by local human populations.

KEY WORDS anthropogenic disturbance; ecosystem impacts; tropical dry forest; soils; India

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INTRODUCTION

Indian forests in the *Eastern Himalayan* and *Western Ghats* regions are among the world biodiversity hotspots (Myers *et al*., 2000), in recognition of their high degree of biodiversity, endemism, and threats to the same. Much of India's biodiversity is protected within a country-wide network of 593 wildlife reserves and national parks (Madhusudan, 2005). There are enormous anthropogenic pressures on these reserves from communities residing both within and on the fringes of these reserves. Over five million people have been estimated to reside within these reserves (Kothari *et al*., 1995). Indian forests have been used by communities over millennia for a variety of uses and activities (Lele and Hegde, 1997; Shankar *et al*., 1998a). Of these, livestock grazing, fuelwood/fodder extraction, and burning represent historic and continuing uses of the forest (Banerjee, 1995; Bhat *et al*., 2001; FAO, 2006b). At the same time, these activities represent substantial pressures on the forest resource base. Grazing livestock are quickly followed by fuelwood extraction. Once livestock graze and open up the vegetation in an area, fuelwood collectors follow and cut down the standing woody vegetation. Annual low-intensity fires represent burning practices that continue today, usually to promote grasses that are used locally as fodder or household articles (Saha, 2002; Kodandapani *et al*., 2004). As a result, livestock grazing, fuelwood/fodder extraction and burning are recognized as 'chronic disturbance' (Singh, 1998) that can have substantial impacts on the entire forest ecosystem—including impacts on vegetation (Tilman and Lehman, 2001), fauna (Bawa and Seidler, 1998; Terbrogh, 1998), soils (Bruijnzeel, 2004) and hydrologic processes (Giambelluca, 2002; Bonell and Molicova, 2003). At regional scales there are possible links to climate change primarily through changes in radiative properties of replacement land cover (National Research Council, 2005).

However, quantitative studies on the impacts of forest disturbance in India were relatively few until fairly recently (Shahabuddin and Prasad, 2004). Of these, the majority has focused on the impacts on vegetation alone (e.g. Shankar *et al*., 1998b; Madhusudan, 2000; Sagar

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et al., 2003; Kumar and Shahabuddin, 2005). Research is scarce on the impacts of degradation on soils (e.g. Sahani and Behera, 2001), or on soils as well as vegetation (e.g. Pandey and Singh, 1991). Existing research on the impacts on soils confirms the negative impacts of disturbance on clay content, organic matter and soil moisture (Pandey and Singh, 1991; Sahani and Behera, 2001). With the opening of the forest canopy, increased throughfall can increase the vulnerability of soils to erosion. Along with the actual removal of biomass, increased erosion also results in a net loss of nutrients and organic matter. Compaction due to trampling can increase the bulk density and reduce infiltration, causing an increase in surface runoff and increased soil aridity. Impacts of disturbance on watershed-scale hydrology have not been investigated, being limited to controlled deforestation/afforestation experiments in small, humid headwater watersheds (e.g. Sikka *et al*., 2003). Similarly the Indian literature is scarce on the impacts of trails, another land use to be commonly found in forests. Trails inside forest areas, both those maintained and used by Forest Departments as well as those created by livestock, can substantially alter soils and hydrologic processes. Field experiments on unpaved roads in tropical forests of southeast Asia have demonstrated that they effect stream flow by generating Hortonian overland flow on the road surface (Ziegler *et al*., 2000), with varying effects on watershed stream flows (Cuo *et al*., 2006).

There are virtually no investigations on the impacts of disturbance on soils, vegetation and hydrology together. This research addresses this knowledge gap in a deciduous forest in the *Bandipur National Park* (*BNP*), India. Two companion studies report the impacts on vegetation (Mehta *et al*., 2008, this issue), and watershed scale hydrology (Krishnaswamy, personal communication). This paper reports the impacts of forest disturbance on surface soil properties (physical, hydraulic and nutrient) in *BNP,* India. The objectives of the present study were:

1. To investigate key soil characteristics (physical, hydraulic, nutrient) along a degradation gradient: How are these characteristics related to degradation?
2. To compare key soil characteristics (physical, hydraulic) on and off trails, and estimate trail densities within research areas: How do trails impact these characteristics?

STUDY AREA

Location and biogeographic region

The study area is located in dry tropical forests within four research watersheds in *BNP* (Figure 1). The BNP

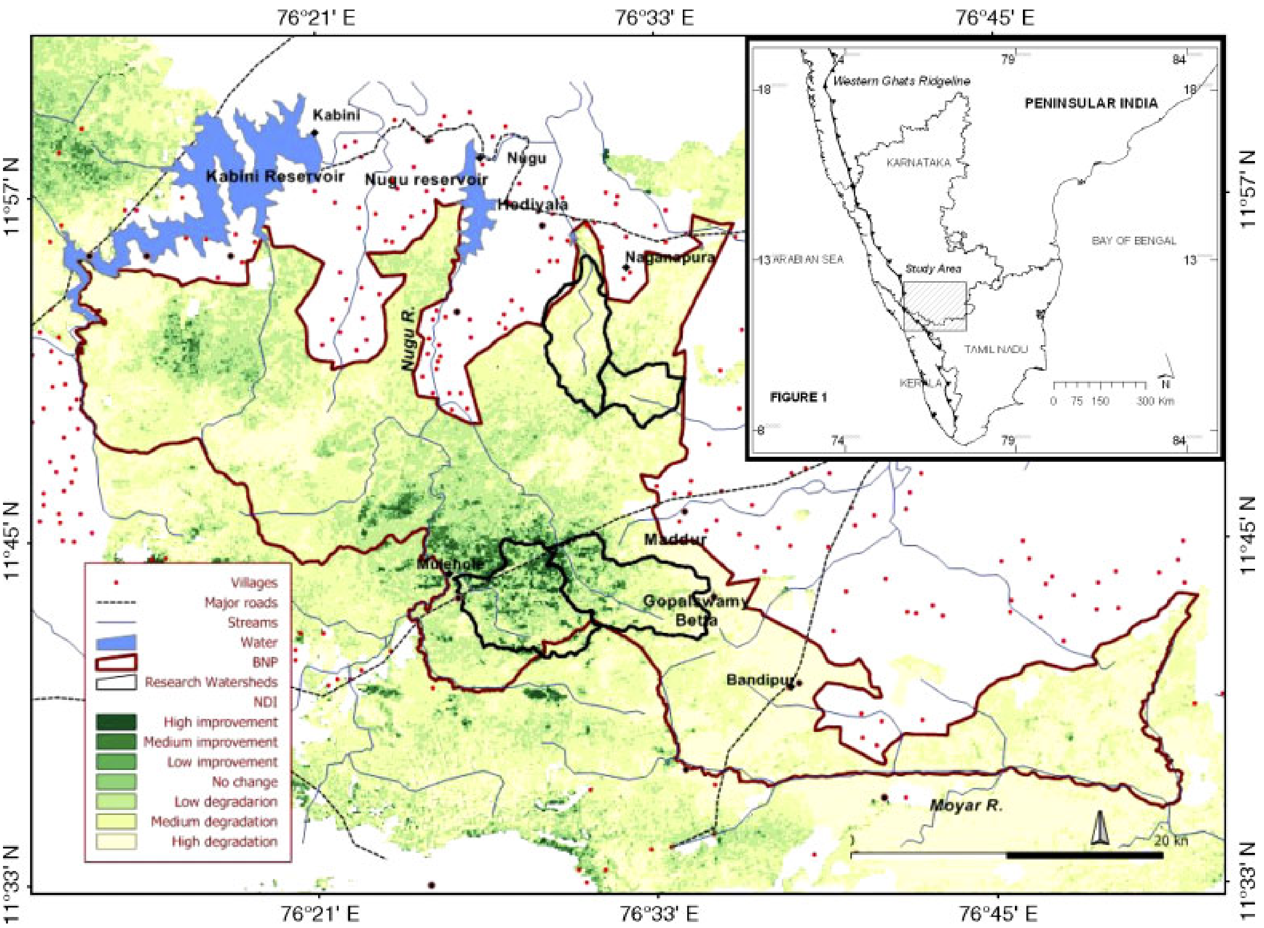

Figure 1. Bandipur National Park. inset: study region.

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(Longitudes 76°12′E–76°53′E, Latitudes 11°35′N–11°58′N) is in the state of Karnataka in Peninsular India. The Park, approximately 874 km^2 in area, is located leeward of the *Western Ghats* mountain range and is a biodiversity hotspot (Figure 1, inset). It is home to 17 critically endangered, endangered and vulnerable plant and animal species (2001 International Union for Conservation of Nature (IUCN) Red List, www.redlist.org), and is one of the Project Tiger conservation areas in the country. The Park supports high densities of large herbivores including the gaur (*Bos gaurus*), the Asian elephant (*Elephas maximus*), and large carnivores such as the tiger (*Panthera tigris),* leopard (*Panthera pardus*) and dhole (*Cuon alpinus*). BNP lies in the sub-humid transitional zone between the humid high elevation backslopes of the *Western Ghats* and the semi-arid Deccan plateau interiors (Bourgeon, 1989 p 37–56). Elevations in BNP range from a low of 700 m on the western border, to a maximum of 1450 m at *Gopalswamy Betta* in the central portion of the park. The topography is gently undulating except for the *Moyar* river gorge on the south-east border. Drainage is predominantly northward and eastward. The only perennial rivers are the *Kabini* and *Moyar* rivers.

Climate

The average annual rainfall ranges from 900 to 1200 mm within the Park (Pascal, 1982). The climate is tropical savanna, hot and seasonally dry (IMD, 1984). Mean minimum and maximum daily temperatures are 15 °C and 35 °C respectively. The dry season extends from the end of December to the end of March (Pascal, 1982; Devidas and Puyravaud, 1995). Rainfall is trimodal, occurring as convectional pre-monsoon storms (March–May), the south-west monsoon (June–September) and the north-east monsoon (October–December), with most rainfall in October (Devidas and Puyravaud, 1995). Relative humidity is generally high during the south-west monsoon (70%), and low (30%) from January to April in the afternoons. Figure 2 shows the monthly rainfall for the *Bandipur* station over 67 years, with annual average of 905 ± 284 mm (mean ± 1 s.e). Annual potential evapotranspiration (PET) is approximately 1550 mm. Rainfall frequency analysis was conducted using the 67-year daily rainfall record and the intensity-duration-frequency relationship derived for southern India, listed in Kothyari and Garde (1992).

Geology and soils

Soils data were assembled from a variety of published sources to establish the best understanding possible of the baseline soil properties and their spatial distribution in the study region. The BNP falls in the granite-gneiss complex of the Archaean (Peninsular gneiss) group, the chief rocks being gneisses, granites and charnockites. On the basis of coarse scale soil maps of the region (Bourgeon, 1989; Shiva Prasad *et al*., 1998), soils in the research watersheds are alfisols (U.S. Department of Agriculture (USDA) classification) between 1 and 1·4 m deep with ustic soil moisture regime, with minimum horizonation (haplic), and are well drained. Published data on several soil profiles that fall within or in close proximity to our research watersheds (Ferry, 1994 p 190–193) reveal that surface soils are generally sandy clay loam with underlying argilic horizons of high to medium base saturation (BS) and coloured deep red with iron oxides. Soils are moderately acidic ($pH_{KCl} \sim 5{\cdot}3$), with a cation exchange capacity (CEC) of approximately 20 cmol/kg, BS above 70% and minimal Al, Mn acidity.

Vegetation

On the basis of extensive ground surveys, satellite data and bioclimatic maps of the *Western Ghats*, vegetation in BNP has been classified as dry deciduous woodland to savanna woodland forests of the *Anogeissus latifolia-Tectona grandis-Terminalia tomentosa* type (Pascal, 1982). Most researchers in the area believe that the current vegetation represents degraded stages of

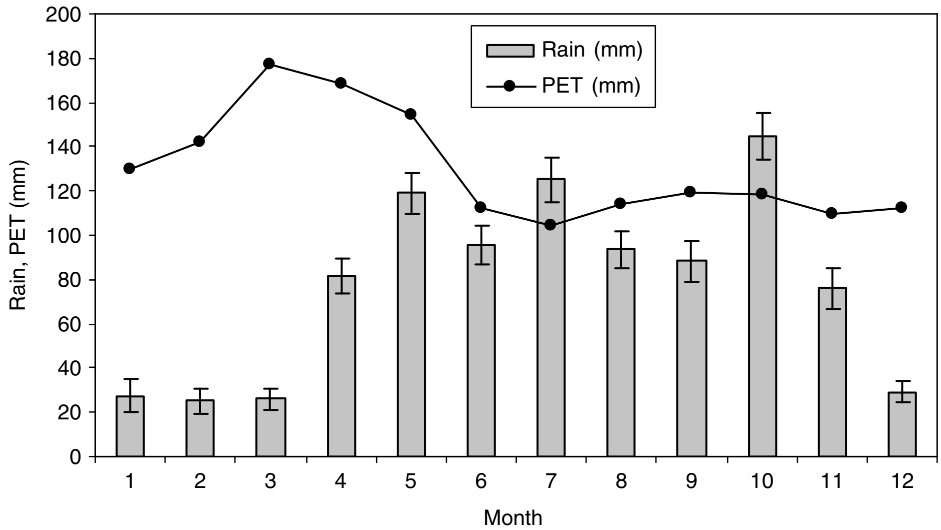

Figure 2. Monthly rainfall and PET at Bandipur. Error bars are 1 SE.

succession, varying from a savanna-woodland to low-discontinuous thickets. Intense overgrazing and lopping of branches has been theorized to convert the tree savanna into 'clump thickets', with the selection of thorny and unpalatable species (Pascal, 1988 p 291–293). These 'clump thickets' and stunted scrub forests can be found extensively along the northern and eastern boundaries of BNP. Grasses belong predominantly to the *Cymbopogon* and *Taeremides* sp. Grass heights and cover are noticeably low and sparse in the degraded northern borders of the Park. The Park falls within a region of the *Western Ghats*, which recent studies have shown are undergoing rapid forest cover losses.

Community and land use

Unlike many other protected areas in the country, there are no human settlements within the boundaries of BNP (Madhusudan, 2005) and all anthropogenic pressures—primarily livestock grazing and fuelwood removal—on the park originate from the villages along its northern flank. Over 100 000 cattle from nearly 180 villages graze in the buffer zone of BNP's northern fringes (Lal *et al.*, 1994). The current density of livestock along the northern boundary is estimated as 236 animals/km^2 (Madhusudan, 2005). The immediate communities on the park boundary closest to the (northern) research watersheds include six villages and tribal hamlets. Of the 758 households, 455 own landholdings averaging less than 2 hectares per household (data courtesy of Dr S. Lele, *Centre for Interdisciplinary Studies in Environment and Development* (CISED)). Cattle grazing and fuelwood collection occurs within protected forest areas, while small scale farming is practiced just outside park boundaries. Until recently, this use of the forest could be qualified as subsistence use with local village communities as the consumers. However, Madhusudan (2005), in a study on the impact of grazing on vegetation in BNP, has documented the intensification of grazing practices since the 1990s, linked to the export of cattle dung as manure to the neighbouring coffee growing district. This demand for dung from a non-local source, in turn driven by global coffee markets has converted cattle dung from a local subsistence agriculture resource to a commercial export to neighbouring coffee estates. As a result, the pressure on the northern boundaries of the Park has substantially increased in the last decade.

MATERIALS AND METHODS

Sampling framework

Sample locations were nested within four watersheds in BNP that had been previously identified and instrumented for a study on the impacts of forest degradation on rainfall-stream flow response (Krishnaswamy *et al.*, 2006). A degradation index based on satellite imagery derived vegetation indices—the change in Normalized Difference Vegetation Index (NDVI) between 1973 and 1999—served as the basis of watershed selection in protected and degraded parts of BNP. See Krishnaswamy *et al.* (2006) for details. Figure 1 shows the NDVI-based change classification map for BNP and the research watersheds within which samples were collected. Table I summarizes the characteristics of the four watersheds.

A 1 km × 1 km grid was laid over the entire park and five grids were randomly selected for each of the four watersheds. Surface soil sampling, infiltration tests and vegetation sampling were conducted at 10 locations within each grid for a total of 200 samples. Using a topographical sheet (Survey of India (SOI); 1:50 000 scale) of the area and a GPS unit, we used a four-wheel-drive jeep to travel to each grid on cattle or jeep trails. Each sample location was selected at random distances on either side of the trails that intersected any part of the selected grid subject to considerations of safety. Among other wildlife, elephants or signs of elephants were encountered at 150 of the 200 locations, and a tiger was spotted on two occasions. These considerations prevented us from venturing more than 500 m away from the access trails within the forest. Samples were collected in the post-monsoon season, between November 2005 and March 2006.

For the trails campaign, 20 locations on either jeep or cattle trails were chosen, for each of which off-trail measurements were made approximately 50 m away inside the forest. These 40 locations spanned the general region of the study watersheds. The impacts of jeep and cattle trails were not separately quantified primarily because jeep trails, especially in northern watersheds, are frequently used by cattle and herders. Figure 3 shows the Digital Elevation Model (DEM) of the research watersheds with the selected grids and sample locations overlaid. The DEM (90 m resolution) source for this dataset was the Global Land Cover Facility (http://www.landcover.org). Also marked are the locations of villages digitized from SOI topographic sheets showing their high density along the BNP boundary.

Table I. Characteristics of research watersheds.

Watershed (area, km^2)	Elevation (m)			Slope (degrees)			Topographic index[a]		
	Mean	Median	Range	Mean	Median	Range	Mean	Median	Range
Hebhalla (41·8)	1029	991	892–1450	8·8	6·1	0–45	8·0	7·7	5·0–16·7
Hediyala (27·7)	872	824	757–1124	5·5	3·7	0–40	8·6	8·1	4·9–17·6
Muntipur (14·2)	954	950	901–1042	4·7	4·3	0–25	8·4	7·9	5·7–16·8
Soreda (41·4)	918	911	840–1107	5·1	4·3	0–33	8·4	8·0	5·6–16·7

[a] Topographic index = ln(a/s). a, flow accumulation per unit length; s, fraction slope.

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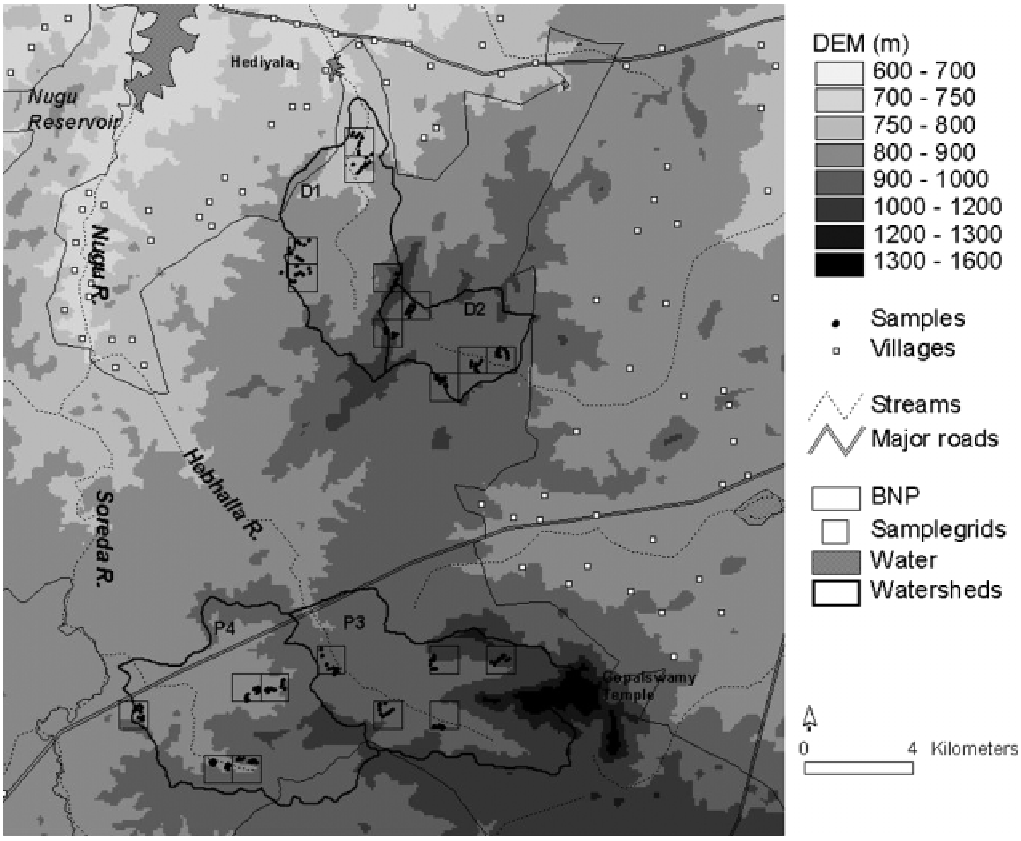

Figure 3. Research watersheds and sample locations. Watersheds are: (D1) *Hediyala*; (D2) *Muntipur*; (P3) *Hebhalla*; (P4) *Soreda*.

Sampling methods and laboratory analysis

Undisturbed soil samples were collected from the surface using steel soil cores of 2 cm diameter and 2 cm height. These samples were used to calculate bulk density and volumetric moisture content. In addition, a composite disturbed sample was taken from the surface soil using a Hoffer soil sampler (Ben Meadows Co., Janesville WI) from five locations within 1 m radius of the undisturbed sample. These samples were air-dried and analyzed for texture, CEC, exchangeable bases, soil organic carbon (SOC) and pH. Infiltration tests at each of the 200 locations were conducted *in situ* using a constant head mini-disk infiltrometer (Zhang, 1997) to measure the hydraulic conductivity at 0·5 cm suction (Decagon Devices Inc., Pullman WA). Johnson *et al*. (2006) used this device in a similar fashion in headwater basins in the Brazilian Amazon, interpreting the measurements as saturated hydraulic conductivity since a suction of 0·5 cm (0·05 kPa) is indistinguishable from saturation on a soil water characteristic curve. A suction of 0·5 cm corresponds to matrix flow in pore sizes less than approximately 6 mm. In this study, the mini-disk infiltrometer measurements at 0·5 cm suction are considered to correspond to near-saturated hydraulic conductivity accounting for all but the largest macropores, and are reported as K_S.

Observations of the field disturbance in the plot were recorded and combined into a Field Disturbance index (FDI). The FDI comprised of presence/absence (1/0) observations of five indicator variables: (i) T - trails (cattle or jeep); (ii) C - cut and/or broken stems; (iii) D - cattle dung; (iv) P - people; and (v) F- fire. For each plot, FDI was calculated as $FDI = T + C + D + P + F$. The choice of indicator variables was informed by literature concerning anthropogenic impacts on vegetation ecology in Indian forests (Shankar *et al*., 1998b; Kumar and Shahabuddin, 2005).

For the trails campaign, undisturbed surface soil samples were taken at the 20 on-trail and 20 off-trail samples using steel cores of 2 cm diameter and 2 cm height. These samples were used for calculating bulk density. Infiltration was measured using two instruments. Five measurements of K_s using the mini-disc infiltrometer were taken at each location and averaged. One measurement at each location was also taken with the CSIRO Disc Permeameter (Commonwealth Scientific and Industrial Research Organization, Australia)—these are reported as K_{csiro}. The CSIRO Disc Permeameter measurements (K_{csiro}) incorporate the influence of soil matrix as well as macropores, whereas the mini-disc infiltrometer measured K_s is mainly influenced by the soil matrix. Given the differences in operation between the two instruments, our intention in using the two instruments was not to relate the two measurements directly, but to answer the question—is both micro- and macro-porosity influenced infiltration affected on trails? Use of the CSIRO disc permeameter in the intensive soil sampling at 200 locations within the forest was impractical because of its bulk, water requirements and time constraints.

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The density of trails in research watersheds was estimated using a 5 m resolution Indian Remote Sensing Satellite (IRS-P6) LISS 4 satellite image (dated 6 May 2005) of the study area. The trails in research watersheds, visible on the satellite image, were mapped by on-screen digitizing after georeferencing the image using IDRISI Kilimanjaro Geographic Information System (GIS). Where obscured by cloud cover, or in some cases not as clearly visible due to canopy cover, GPS readings, SOI maps and a 24 m resolution IRS LISS3 image from 27 February 2006, were used to complete the trails mapping. Trail widths, especially for jeep trails, are fairly uniform. Fifteen measurements of trail widths were taken in different parts of BNP to estimate an average trail width.

Laboratory analysis

Soil analyses were performed by *Mamatha Analytical Laboratory* in Bangalore, India. Soils were air-dried and sieved through a 2 mm sieve before analysis. Soil samples were analyzed for pH (1 : 1 in water and 0·01 M KCl), 1 M KCl-exchangeable acidity and Al using NaF titration (Thomas, 1982). CEC was measured using pH 7 buffered ammonium acetate (Chapman, 1965). Cations (Na, K, Ca, and Mg) were extracted using the buffered solution and analyzed by atomic absorption spectrophotometry. CEC determination at buffered pH can be an overestimate due to pH dependent charges especially in soils high in organic matter and low in pH (Skinner *et al.*, 2001). At low pH (<5·5), Al can also be exchangeable. The measured soil pH (1 : 1 water) was only mildly acidic (Table II). The pH of 183 of the 200 soil samples was above 5·5. The measured KCl-acidity was also very low (mean of 0·07 cmol/kg). Hence CEC is reported as analyzed using buffered pH. BS is the sum of exchangeable base cations divided by CEC. SOC was analyzed using the modified Walkley–Black method (Walkley and Black, 1934; Allison, 1960). Texture was determined using the pipette-gravimetric method. Bulk density was measured using the intact soil cores. Wet weights were measured before drying the soils at 105 °C until the dry weight stabilized in 2 to 3 days. Bulk density and volumetric moisture contents were calculated. The soil-water characteristic curve for 58 of the 200 surface soils was determined using pressure-plate apparatus (Soilmoisture Equipment Corp., Goleta, CA, USA) at the National Institute of Hydrology in Belgaum, India.

Data analysis

All analyses were conducted using R statistical software (R Development Core Team, 2006). CEC and infiltration were analyzed as key response variables. CEC was chosen as it is an important soil property describing nutrient availability for plant growth. The saturated hydraulic conductivity K_S, as measured by the mini-disk infiltrometer, was chosen to represent infiltration capacity of the soil matrix. The analytical approach consisted of building several general linear models (GLM) with a suite of soil covariates that could explain the variability in the response variable. Covariates included for model selection included those properties known from basic soil sciences to impact the response variable (Brady and Weil, 1999). For CEC, model covariates that were tested were pH, clay content and SOC. For K_s, bulk density and clay content were tested. In both cases, terrain variables (elevation, slope and topographic index) were also included for model selection. The best model was chosen after step-wise addition of covariates with and without interaction. The relationship of significant covariates with FDI was then assessed. Hence any direct relationship between disturbance and the key response variables is interpreted through relationships of significant soil covariates with disturbance.

Spatial autocorrelation in the response variables was tested using Moran's I statistic (Cliff and Ord, 1981). Two approaches were tested for handling spatial autocorrelation. First, a resampling procedure was used, wherein 1000 iterations of the linear models (LMs) were carried out, with only one sample randomly chosen from each grid for each iteration. With 20 data points per iteration, the different LMs were fit and diagnostics recorded for each iteration. The best model and corresponding

Table II. Surface soil characteristics.

Variable	Mean (±1 sd)	Range	CV (%)
Soil bulk density (g/cm^3)	1·38 (0·13)	1·01–1·73	9·5
% Soil organic carbon	2·44 (1·04)	0·08–4·92	42·6
% Clay	22·0 (6·94)	6·60–38·40	31·5
% Sand	62·1 (10·57)	38·4–86·6	17·0
% Silt	13·8 (5·00)	4·0–31·6	36·2
CEC (cmol/kg)	17·6 (7·87)	3·20–39·40	44·6
Exch. acidity (cmol/kg); $n = 190$	0·07 (0·04)	0·01–0·2	57·1
% Base saturation; $n = 188$	67·99 (21·14)	14·9–98·2	31·1
pH (KCL)	5·33 (0·39)	4·54–6·4	7·3
pH (water); $n = 199$	6·1 (0·39)	4·84–7·1	6·3
K_s(mm/h)	31·3 (24·68)	0·57–161·6	78·8
Ca (cmol/kg); $n = 197$	7·6 (3·79)	0·8–22·4	49·9
Mg (cmol/kg)	3·61 (2·12)	0·1–10·8	58·9
Na (cmol/kg)	0·60 (0·18)	0·3–1·4	30·0
K (cmol/kg)	0·44 (0·19)	0·16–1·64	43·4

significant covariates were selected on the basis of the mean performance of each model over the 1000 tests, using p-values of parameter estimates, Akaike Information Criteria (AIC) and AIC weights criteria (Akaike, 1973; Hobbs and Hilborn, 2006). The second approach was to explicitly model the spatial autocorrelation in the residuals using a weighted least squares (WLS) regression model, with the weight matrix taking on the structure of the covariance matrix of residuals (Kutner *et al.*, 2004 p 421–431). An omnidirectional, spherical variogram was used to model the covariance with sill and nugget parameters of 20 and 0 $(\text{cmol/kg})^2$ respectively and a range of 2000 m. Parameters from the WLS model were compared with a LM based on all 200 samples without accounting for autocorrelation, to determine the impact of autocorrelation. The best model selected from each approach, and respective model parameters were compared before a final model was adopted.

Soil properties were compared with FDI by treating FDI as a continuous variable, except when sample size was small, as was the case with available water capacity (AWC) and saturated moisture content (SMC). AWC and SMC, calculated from the soil moisture characteristics on 58 samples, were compared with disturbance by categorizing the 58 samples into two groups. This binary classification was based on K-means clustering of all 200 samples using the FDI indicator variables into two groups ('degraded' and 'protected'). K-means clustering is a non-hierarchical method that produces a single partition optimizing within group homogeneity (Legendre and Legendre, 1998). Significant differences in AWC and SMC between samples from these two groups were determined using t-tests.

RESULTS

Field disturbance index

Cut and/or broken stems(C) were most frequently observed, in 55% of the plots. Jeep or cattle trails (T) were encountered in 40% of the plots. Signs of fire (F) were observed in 20·5% of the plots, cattle or cattle dung (D) in 15·5% and people sighted (P) in only four of the plots. The combined disturbance variable FDI itself ranged from 0 to 4, with no disturbance indicator observed in 29% of the plots, one indicator observed in 27·5% of the plots, two indicators observed in 26%, three indicators in 16·5% of the plots and four indicators in only two of the plots. There were no plots in which all five indicators were observed. The livestock indicator (D) was probably under-counted, because the dung deposited by livestock inside the forest boundaries is removed by herders and sold to coffee estates in the neighbouring district (Madhusudan, 2005). Similarly, people sightings (indicator P) were also probably under-counted because of the evasive behaviour of people who are illegally within the Park. The results were not affected by exclusion of this variable from the combined FDI disturbance index.

The distribution of FDI from the 50 samples in each of the four watersheds indicates that the two northern watersheds ($D1$ and $D2$, mean FDI of 2·26 and 1·98 respectively) are more degraded than the two southern watersheds ($P3$ and $P4$, mean FDI of 0·42 and 0·66 respectively). This was confirmed with K-means clustering performed on FDI. Cluster 1 (total samples = 113) contained 91 out of the 100 sites sampled in the two northern watersheds (D1 and D2). Cluster 2 (total samples = 87) contained 78 of the 100 sites sampled in the two southern watersheds (P3 and P4). As a result, the two northern watersheds were grouped together as 'degraded', and the two southern watersheds as 'protected'.

Soil characteristics

Soils were mostly sandy clay loam (57% of the samples) with a mean clay content of 22%. According to USDA classification 29·5% of the soils were sandy loams. Soil colour was predominantly black or very dark grey. More than 50% of the samples were of yellow–red hue (10YR). Soil colour was more variable (lighter in value) in the more degraded northern watersheds. Surface soils in the more degraded watersheds were mostly of weak, fine granular structure, while in the more protected southern watersheds they were largely of moderate, coarse granular structure. Soil bulk density averaged 1·38 g/cm^3. The average SOC was 2·44% with a high coefficient of variation of nearly 43%. CEC averaged 16·64 cmol/kg, also with high variability. BS was moderately high at 67·99 cmol/kg. Soils were moderately acidic with an average pH_{KCl} of 5·33 and low variability. The average infiltration, as measured by K_s, was 31·3 mm/h. Hydraulic conductivity was the most variable among the soil characteristics measured, with a coefficient of variation of nearly 79%. See Table II for a summary of the soil characteristics. Unless otherwise mentioned in the table, the summary is for all 200 samples.

Soil nutrient availability

The effect of disturbance on nutrient availability was investigated with CEC as the key response variable. Figure 4(a) shows that CEC is negatively correlated with FDI (Pearson's $r = -0{\cdot}58$, $p < 0{\cdot}05$). CEC decreases with increasing disturbance levels. An explanation for this relationship can be found through the impacts of disturbance on soil covariates that directly impact CEC. In all three modeling procedures (resampling, WLS and LM), the final model that best captured CEC variation was an additive model with SOC and clay. Despite the data being spatially autocorrelated (based on Moran's I statistic), there was no significant difference between model parameters determined by the WLS and LM procedures. Model coefficients (b0, b1, b2 respectively) were −2·73, 3·85 and 0·50 in the WLS model; and −2·75, 4·35, and 0·43 for the LM model. Details of parameter estimates from all three models are presented in Table 2·3 in Mehta (2007). We conclude that the

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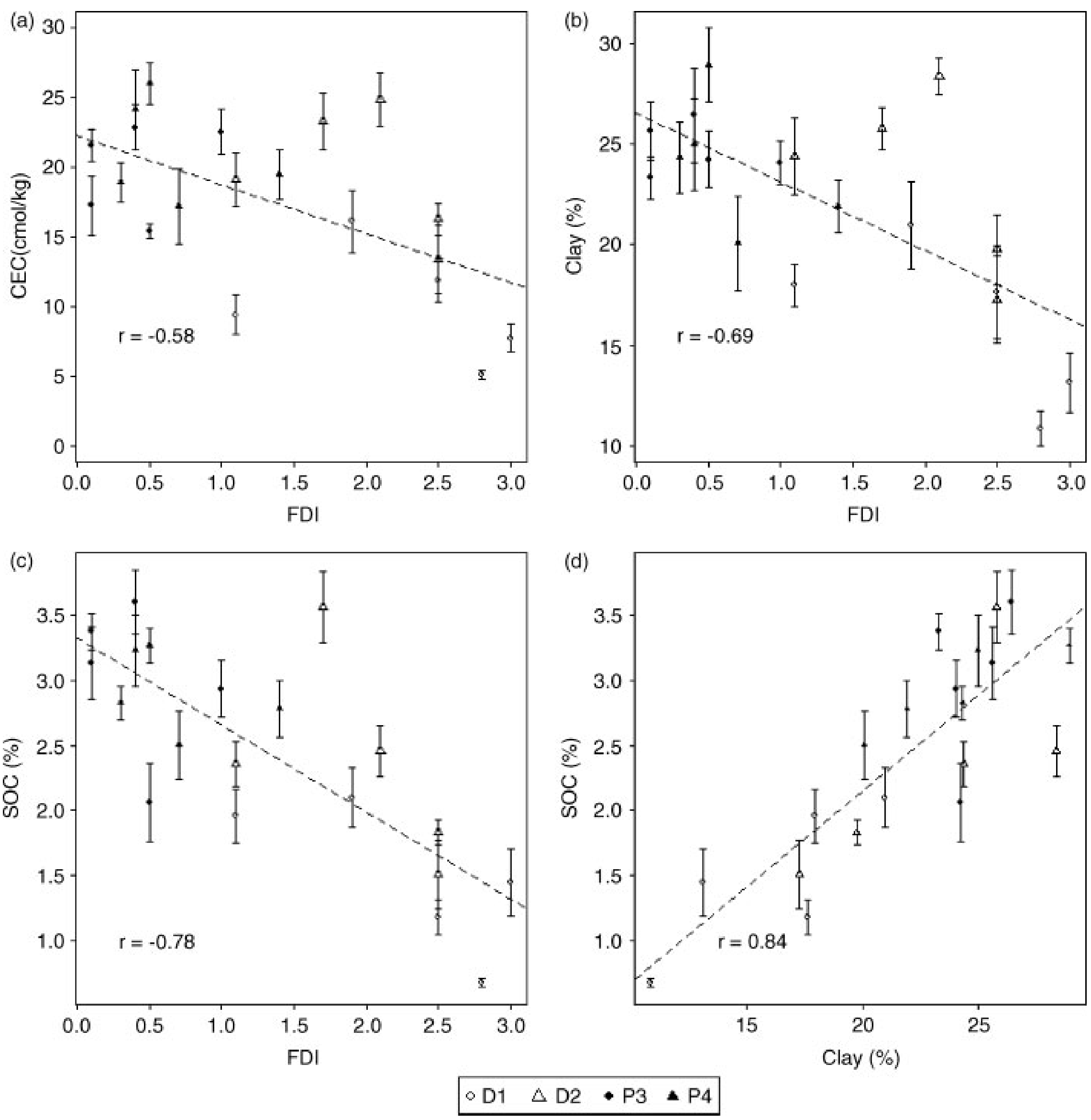

Figure 4. Scatterplots of soil properties versus FDI. (a) CEC and FDI (b) Clay and FDI (c) SOC and FDI (d) SOC and Clay. Dotted lines are linear fits. Each point in a–d is the grid-averaged value ($n = 10$). Error bars are 1SE.

effects of spatial autocorrelation on model results were not substantial and adopt the LM model below:

$$\mathrm{CEC} = -2{\cdot}75 + 4{\cdot}35 \times \mathrm{SOC} + 0{\cdot}43 \times \mathrm{Clay}$$

The model was statistically significant ($p < 0{\cdot}0001$) and accounted for 75% of the variability in CEC over all 200 samples. Figure 4(b) and (c) shows that the significant covariates explaining CEC, i.e. SOC and Clay, are individually negatively correlated with FDI. Figure 4(d) also shows that SOC and Clay are positively correlated. Figure 5 shows the modeled and observed CEC. None of the modeling approaches included the terrain variables in the final set of significant covariates. We conclude that soil nutrient availability for plant growth is negatively impacted by disturbance, through the negative impact of disturbance on soil organic matter and clay content.

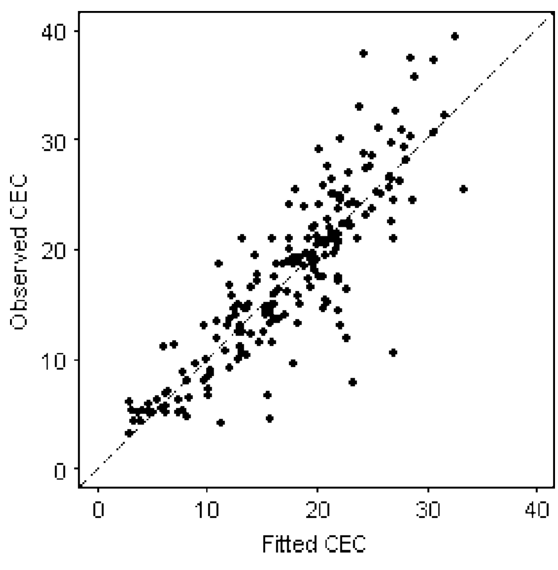

Figure 5. Modeled and observed CEC.

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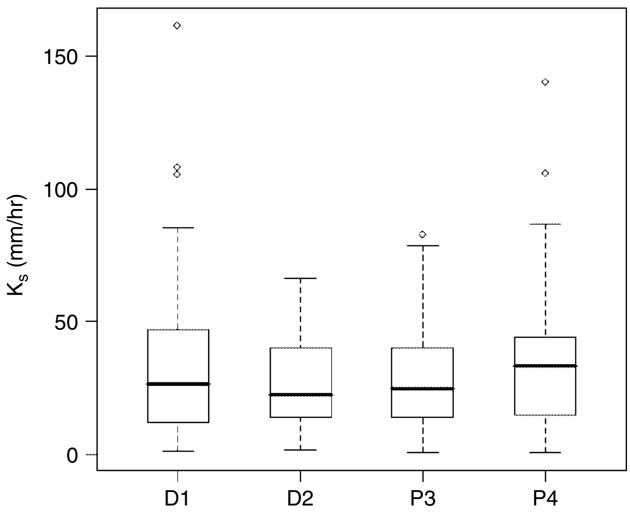

Figure 6. Boxplots of hydraulic conductivity by watershed.

Influence on soil hydraulics: infiltration

The average hydraulic conductivity K_s was 31·3 (± 24·7 sd) mm/h, with the highest variability of nearly 79% (Table II). As is reported in the literature, hydraulic conductivity observations are usually positively skewed, and exhibit high spatial variability. Even discounting spatial autocorrelation, no soil covariates could adequately describe the variability in K_s. An additive model with bulk density and texture was significant at the 5% level but could account for less than 9% of the variability in K_s. Bulk density was not significantly related to FDI either, the overall variability in bulk density being the lowest. Further, using an ANOVA model, no significant differences in K_s among the four watersheds could be discerned. Figure 6 and Table III summarize the K_s data for each watershed. The data could not provide any significant evidence that surface infiltration is impacted by disturbance.

Influence on hydraulics: AWC and SMC

Fifty-eight of the samples were analyzed to determine soil moisture characteristics. Thirty-two samples were from the northern (relatively) degraded watersheds D1 and D2, and 26 samples were from the southern (relatively) protected watersheds. SMC, and AWC (computed as the difference between field capacity (0·3 bar) and wilting point (15 bar) moisture contents), were compared between the degraded and protected watersheds with a pooled variance two-sample t-test. AWC in the degraded watersheds (9·2% ± 2·8% sd) was significantly less than AWC in the protected watersheds (11·1% ± 3·3% sd) ($p < 0{\cdot}001$, $t = -2{\cdot}42$, df = 56). SMC was also significantly less in the degraded watersheds (29·1% ± 6·9% sd) than the protected watersheds (35·3 ± 7·5% sd) ($p < 0{\cdot}009$, $t = -3{\cdot}27$, df = 56). Soil moisture characteristics, grouped by degraded (D) and protected (P) watersheds, are displayed in Figure 7.

Table III. Summary of hydraulic conductivity by watershed.

Watershed	Mean	Sd	Median	IQR
Hebhalla	29·9	21·1	24·9	14·3–39·3
Hekkon	34·5	31·5	26·4	12·6–46·2
Muntipur	26·6	16·2	22·3	14·0–39·1
Soreda	33·9	27·0	33·5	14·9–44·2

Sd, standard deviation; IQR, Interquartile range. All values in mm/h. Sample size = 50 per watershed.

Impacts of trails

Infiltration and bulk density. Table IV and Figure 8 summarize the results of trail measurements. A two-sample t-test with unequal variances was conducted on the log transformed K_s data, which were slightly skewed. Log transformed K_s measured on trails was significantly less than that off the trails ($t = 5{\cdot}4$, df = 37·62, $p < 0{\cdot}0001$). The K_{csiro} data were more positively skewed. A two-sample t-test with unequal variances was performed on the log-transformed K_{csiro} data. K_{csiro} measured on trails was also significantly less than K_{csiro} off the trails ($t = 7{\cdot}03$, df = 35·7, $p < 0{\cdot}0001$). Reduction of infiltration on trails can be attributed to compaction. This hypothesis was tested by using bulk density as a measure of compaction. Figure 8 shows the boxplots of soil bulk densities on and off trails. A two-sample pooled variance t-test was performed between the bulk densities of on-trail and off-trail samples. The bulk density of soils off the trails (1·29 ± 0·13 sd) was significantly less than the bulk density of soils on the trails (1·42 ± 0·13 sd), at the 1% significance level.

Together, the two instruments—the mini-infiltrometer and disc permeameter—capture both matrix and macrocapillarity related infiltration, respectively. Our results show that infiltration capacity at both scales is negatively impacted by trails, which are compacted. This observed difference in infiltration capacity will likely result in a pronounced difference in Hortonian overland flow generation. For example, on-trail infiltration capacities are approximately equal to the 1-year, 7-h rainfall intensity (~8 mm/h) whereas the same duration storm corresponds to >100-year return period (~30 mm/h) before the off-trail infiltration capacity is exceeded (Figure 9). In other words, 7-h rainfall events will cause the trails to generate Hortonian runoff just about every year but will rarely result in Hortonian flow from the off-trail areas. We show below that trail density is also higher in degraded watersheds, thereby increasing the chances and contribution of Hortonian flow in storm runoff events.

Extent of trails. Figure 10 shows the extent of jeep and cattle trails in each of the four watersheds. Northern watersheds (Figure 10(a)) have a higher density of trails than the southern watersheds (Figure 10(b)). The total lengths of trails estimated were, in kilometers, 108·6, 44·2, 35·3, 44·8 respectively for watersheds D1, D2, P3 and P4 (Table V). Of these total lengths, for each respective watershed, the ratio of cattle to total trails were 84, 68, 30 and <1%. The vast majority of trails in D1 watershed were cattle trails (more than 90 km total length). In

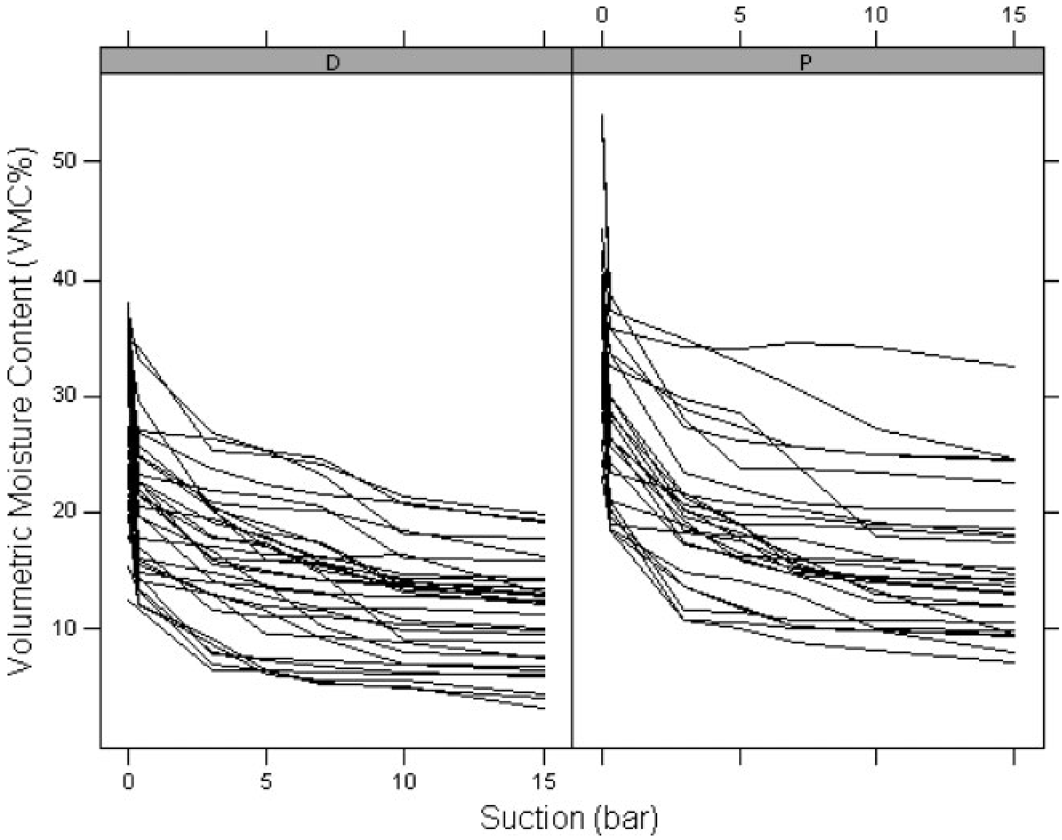

Figure 7. Soil moisture characteristics for 58 samples D = degraded (n = 32); P = protected (n = 26).

Table IV. Infiltration measurements on and off trails.

mm/h	On trails (n = 20)				Off trails (n = 20)			
	Mean (sd)	Skew	Median	IQR	Mean (sd)	Skew	Median	IQR
K_S	8·1 (5·1)	0·75	6·9	3·9–11·5	27·9 (15·9)	0·15	25·3	15·3–39·3
K_{csiro}	15·3 (10·9)	1·8	12·2	8·9–16·7	101·6 (84·9)	1·3	86·1	33·6–138·0

watershed P4, cattle trails were practically non-existent. The northern watersheds taken together had a greater proportion as well as greater length of cattle trails by far, compared to the southern watersheds. The average trail width was 4·51 m (± 0·57 m sd). Assuming an average width of trail of 4·5 m, the maximum density of trails (in D1 watershed) is estimated as 1·8% of watershed area. The density of trails was highest in the northern watersheds.

DISCUSSION

In *BNP*, forest disturbance, quantified as a combined impact of grazing, fuelwood/fodder extraction and fire, has a negative effect on soil nutrient availability through reduction of clay content and soil organic matter of surface soils. No significant effect was discerned on hydraulic conductivity and bulk density within forest areas off the trails. Disturbance also significantly reduced SMCs and AWC. Compaction on trails significantly increases bulk density, thereby strongly and significantly reducing infiltration through both micro and macropores. The density and total lengths of trails were much higher in the northern, more degraded watersheds. In *Hediyala* watershed, they covered nearly 109 km, approximately 1·8% of total watershed area.

We attribute the decrease in clay content and organic matter at degraded sites to the reduction of canopy cover in degraded sites through replacement of tall stature tree cover by short, woody shrubaceous cover (Mehta *et al.*, 2008, this issue). This increases the vulnerability of surface soils to raindrop erosion, with selective erosion of clay particles (Krishnaswamy and Richter, 2002), in turn reducing available and SMC (Brady and Weil, 1999). Simultaneously, active above-biomass removal through grazing and fuelwood extraction impacts soil carbon pools. Our conclusion that anthropogenic disturbances (as opposed to geomorphic differences) are the dominant influences on soils impacts reported here, is supported by baseline soil maps for the study region that characterize the research watershed soils as alfisols (see Introduction). A limitation of these soils maps is their coarse resolution

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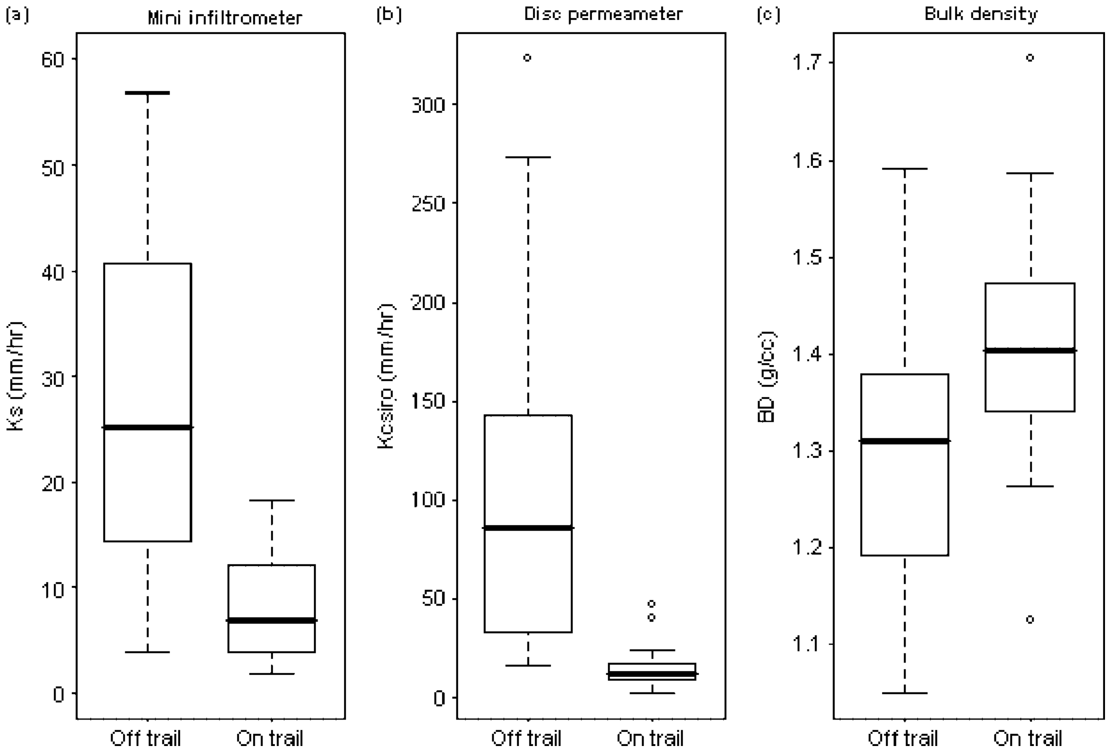

Figure 8. Boxplots of measurements on and off trails (a) K_s; (b) K_{csiro}; (c) Bulk density.

(1 : 50 000 scale). However, we ensured that our sampling strategy and data analysis accounted for terrain differences. Research watersheds spanned the elevation and slope ranges typical of the entire Park, and within each watershed, selected grids spanned low and high elevations (Figure 3 and Table I). Also, terrain variables were included as covariates in model building, but were not found significant.

No attempts were made to elucidate the contributions of individual disturbance indicators to our overall disturbance index FDI. Our goal was to define a collective index that accounted for multiple anthropogenic forest uses efficiently within reasonable constraints of time, budget and personal safety in the forest, while simultaneously allowing the description of degradation as a continuous variable. Moreover, (i) the individual indices are not independent—once livestock graze and open up trails within the forest, fuelwood collectors quickly follow; and (ii) cattle dung is removed from the forest and is an economic resource—hence the indicator D alone would be compromised *relative* to the others. Our results indicate that the indicator 'P' had little value in this study, given the evasive behaviour of non-authorized people in the forest. This variable may be useful in other protected forests where local people do have restricted access. The collective index FDI as formulated here seems to be a robust index in the context of the objectives of this study and specific region.

Implications for large scale impacts

Dry tropical forests account for approximately 60% of the Indian forest cover (WRI, 1996). The disturbance described in this paper is representative of the pressures in dry tropical forests across India. Over two-thirds of India's wildlife reserves are grazed by local livestock (Kothari *et al.*, 1995), with the Forest Survey of India (FSI) estimating that about 77·6% of forest area of the country is affected by grazing of varying intensity (FAO, 2006a,b). Existing studies in other National parks in India have shown similar results as documented here. For example, forest disturbance has been related to decreases in CEC and SOC by Saikh *et al.* (1998a,b); clay content (Pandey and Singh, 1991; Sahani and Behera, 2001) and soil moisture (Pandey and Singh, 1991). Placed in the larger context of widespread forest use, the findings of this local study and similar findings from other forested areas point towards potentially *substantial and wide-spread impacts* on several aspects of ecosystem processes—nutrient/biogeochemical cycling and hydrology in particular. The reduction in soil organic matter and nutrient availability documented in this study are evidence that biogeochemical cycling and soil carbon stocks are directly impacted by forest disturbance. Further evidence is provided by Madhusudan (2005) who details the impacts of the dung economy wherein cattle grazing inside the forest produce dung that is exported out of the forest resulting in continual removal of biomass from the ecosystem.

The impacts on hydrology are evident in this paper in two aspects—(i) the reduction in soil available water capacities in disturbed forest areas along with reduction of clay content; and (ii) reduced infiltration due to compaction on trails. These results reflect the findings of other researchers on the impacts of similar kinds of forest disturbance in the dry tropics (Perrolf and Sandstrom, 1995;

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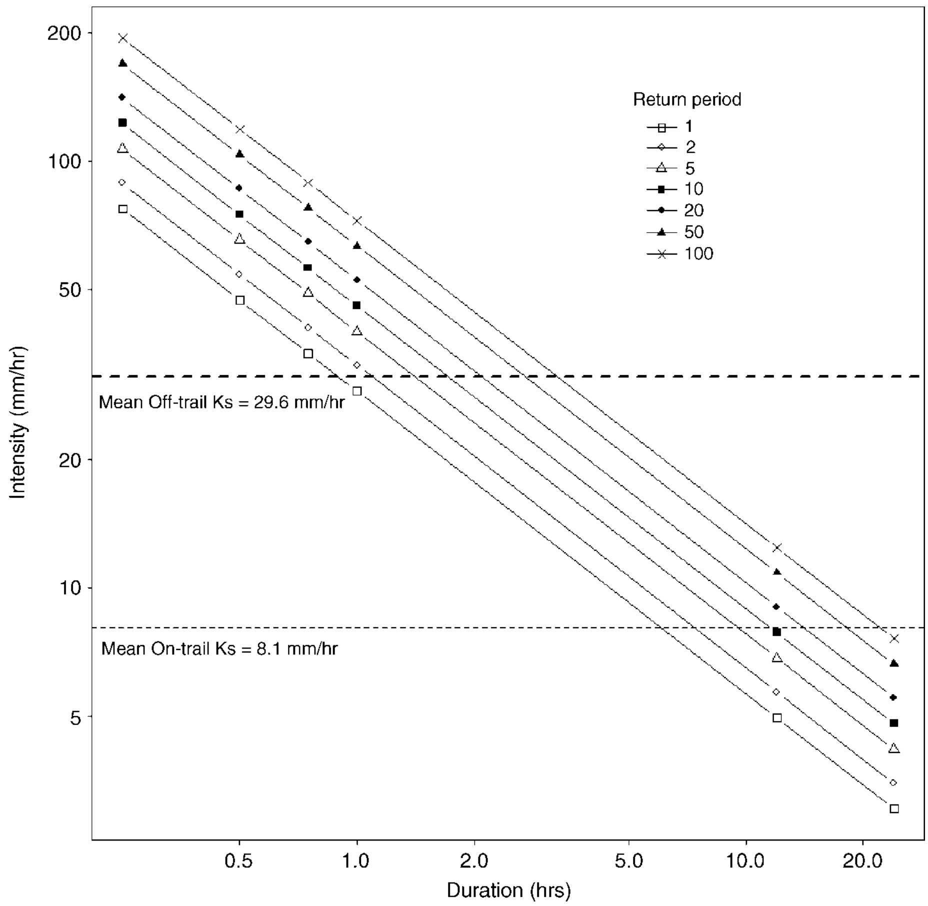

Figure 9. Rainfall IDF curves with infiltration capacity on and off trails. Off-trail data includes samples from both grid sampling and trail campaigns.

Sandstrom, 1995; Bonell and Molicova, 2003; Karambiri *et al.*, 2003). The resulting impacts on watershed scale water yields are challenging to quantify for a number of reasons (see Bruijnzeel (2004) for a relevant review, albeit more focused with controlled experiments on small watersheds in humid tropical forests). Not least of these reasons is the seasonal nature of stream flow as in the research watersheds characterized by zero dry season flow with stream flows events limited to a few during the wet season (Krishnaswamy *et al.*, 2006). The greatest hydraulic impact documented in this study was due to trails. Whereas the mean hydraulic conductivity in the forests was documented as 31 mm/h, K_s on trails averaged only 8·1 mm/h; presenting clear evidence that the chances of overland flow due to infiltration-excess (Hortonian) flows are increased on trails. The 20 K_{csiro} measurements off-trails also indicate that macroporosity is probably a major influence on forest soils infiltration off the trails—mean K_{csiro} is more than three times mean mini-disc infiltrometer (K_s) measurements (Table IV). Limited K_{csiro} sample size prevents generalization of macroporosity effects over the entire forest area. However, the K_s and K_{csiro} results together indicate that dramatically reduced infiltration and increased presence of trails in the more degraded watersheds can be expected to manifest themselves in storm-flow events in the form of greater proportion of quick flow caused by rapid, infiltration-excess overland flow (Bonell and Molicova, 2003; Bruijnzeel, 2004) as has been documented in south-east Asia (Ziegler *et al.*, 2000; Cuo *et al.*, 2006). This hypothesis is borne out from the analysis of several event hydrographs over 2 years in the research watersheds—stream flow events are 'flashier', i.e. contributions of quick flow are greater in the northern degraded watersheds compared to the southern, more protected watersheds (Krishnaswamy, personal communication). Increased event runoff accompanied by increased surface erosion are expected to be the most direct and locally relevant watershed scale impacts of forest disturbance in the study area. Immediate local impacts on water resources are likely to be felt in the cultivated land on the northern boundaries of BNP, where an extensive network of surface irrigation schemes called 'tanks' supply irrigation water for local agriculture. It is plausible that an increased sediment yield from the degraded watersheds would amount to a net negative impact on these water bodies, since runoff and sediment contributions from relatively small proportion of compacted trails and roads are often disproportionately high (Bruijnzeel, 2004).

Researchers have long recognized that forest disturbance of the form described can have substantial impacts on the entire forest ecosystem (Tilman and Lehman, 2001). Despite this, research on impacts on dry tropical forests, especially on the Indian subcontinent, remains scarce. The urgency in addressing this knowledge gap is underscored by the fact that the *Western*

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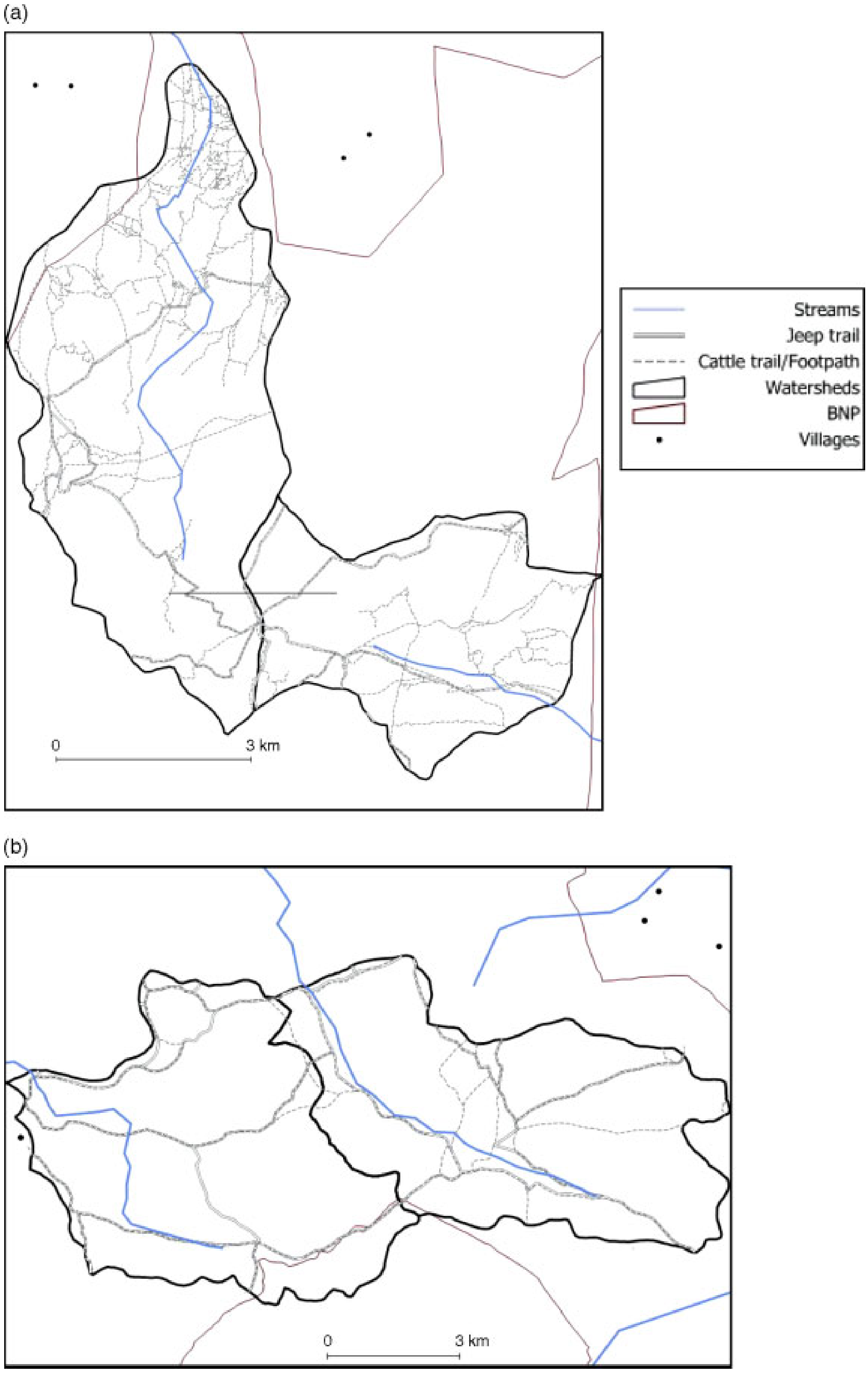

Figure 10. Trails in (a) northern and (b) southern watersheds.

Table V. Density of trails.

Watershed	Length (km)	Density (km^{-1})	% Cattle trail
D1	109	3·9	84
D2	44	3·1	68
P3	35	1·1	30
P4	45	0·9	<1

Ghats form the major watershed of Peninsular India. This is a region that has encountered substantial forest cover loss and fragmentation (Menon and Bawa, 1998; Jha *et al*., 2000; Amarnath *et al*., 2003). Interdisciplinary research on ecosystem functioning in the region, which includes energy, water and nutrient cycling, is necessary for a more comprehensive picture on local and regional ecosystem impacts of widespread forest disturbance of the nature investigated in this paper. This paper describes the impacts on surface soils. Companion studies describe the impact on vegetation ecology (Mehta *et al*. in preparation), and watershed scale hydrology

(Krishnaswamy *et al.*, in preparation). These investigations help set the stage for comprehensive research on the ecosystem impacts of forest disturbance in the Indian subcontinent.

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