

Coupling Field Sampling with Earth Observation Increases Understanding of Tiger Movement and Behaviour

Sonali Ghosh and Richard Lucas

Abstract Tigers (*Panthera tigris*) are critically endangered worldwide, with the geographical range of native populations reduced to less than 7% in the last hundred years. Currently, there are only 6 subspecies residing in thirteen range countries. The main causes of their decline are habitat loss and fragmentation, prey depletion and poaching for the illegal wildlife trade. Addressing these issues has been severely constrained by inadequate spatial information on tiger distributions, movements, habitat preferences and behaviour. Focusing on the Indo-Bhutan Manas Tiger Conservation Landscape (IBMTCL) in the Indian subcontinent (India and Bhutan), this study sought to demonstrate the use of field-based camera traps for providing ground-based observations of tigers and other large cats, namely leopards (*Panthera pardus*) and clouded leopards (*Neofelis nebulosa*), and their prey. These observations were also coupled with classifications of land cover, elevation data and fire observations from Landsat TM and the Terra ASTER and MODIS respectively. The study indicated a large but variable range for individual tigers, a preference of tigers for forest cover and proximity to burned areas (attributed to greater access to prey), and a spatial separation from populations of other large cats. The study illustrates how earth observation data can provide some of the elements needed to better understand how large cats utilise the landscapes they inhabit thereby contributing to efforts aimed at long-term conservation of these endangered species across their range.

Keywords C12 • Tiger • *Panthera tigris* • Carnivores • Royal Manas National Park • Manas National Park • Camera trap • Earth observation • Fire • Topography • Land cover

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Introduction

The tiger (*Panthera tigris*) is the largest and one of the most charismatic and endangered cat species in the world. It is a flagship icon for wildlife conservation, being at the apex of the food chain in the majority of the eco-regions in Asia (Sunquist et al. 1999; Jhala et al. 2008, 2015). The tiger has been held in mythical reverence across the world, is worshipped in certain faiths and religions and is the national animal for India, Bangladesh, Nepal, Malaysia and both North and South Korea. Until the early nineteenth century, nine subspecies (Luo et al. 2004) of tiger were found across Asia, from the Caucasus and the Caspian Sea to Siberia and Indonesia. Three of these subspecies are now extinct; the Bali Tiger (*Panthera tigris balica*), Javan Tiger (*P.t.sondaica*) and Caspian Tiger (*P.t.virgata*). The remaining six occur as fragmented populations in the Russian Far East, northeast China and the Asian subcontinent.

India supports about 70% of the World's tiger population and one of the key areas of importance is the Indo-Bhutan Manas Tiger Conservation Landscape (IBMTCL), which offers a contiguous protected landscape of over 6000 sq km and constitutes the core area of Manas National Park (NP) in India and Royal Manas NP in Bhutan. Between November 2010 and February 2011, a large camera trap survey was conducted in Manas NP and the southern section of Royal Manas NP by organisations in both India and Bhutan. This survey was undertaken to locate, identify and track the movements of individual Royal Bengal tigers (*Panthera tigris tigris*) and two other sympatric species, the leopard (*Panthera pardus*) and clouded leopard (*Neofelis nebulosa*). Landsat-derived classifications of land cover, historical MODIS fire records and spatial information on human development of the landscape were then used in combination with the survey results to provide a better understanding of niche separation as well as influences on the movement and range of these large cat species over the period of observation. Through this approach, the potential contribution of integrated field campaigns and earth observation to supporting management of Tiger Conservation Landscapes (TCLs) was assessed.

Background

Why Are Tigers Endangered?

Whilst once widespread, the range of tigers has been reduced to a mere 7% (less than 1,184,911 km²) of their former geographical range, and approximately 55% of the inhabited landscape is essentially non-tiger habitat (Sanderson et al. 2006). A general compilation of national estimates suggests a global population of approximately 4240 tigers remaining in the wild (Goodrich et al. 2015). The causes for their decline has largely been habitat loss and poaching and the pressures continue to escalate (Sanderson et al. 2006; Dinerstein et al. 2007). They are also vulnerable to

extinction because of their low densities (relative to other mammals, including their prey species) and relatively low recruitment rates (where few animals raise offspring that survive to join the breeding population) (Kerley et al. 2003). Tigers also require large undisturbed landscapes with ample prey to raise young and maintain long term genetic and demographic viability (Seidensticker and McDougal 1993; Karanth and Sunquist 1995; Carbone et al. 1999; Jhala et al. 2008). However, such areas are contracting or becoming increasingly fragmented because of high anthropogenic pressures on natural resources. Whilst India has the world's largest population of wild tigers, it has also suffered the highest range contraction for the species. Poaching is mainly for the supply of organs, bones and hides that are smuggled for use in traditional medicine, mainly into China and south-east Asia (Gratwicke et al. 2008; Nowell 2009).

Efforts to save the tiger started rather late. For example, Project Tiger was initiated in India in 1973 (GOI 2005). However, the strategies used were not time-tested and were also often weak on scientific rigor, partly because of a general lack of baseline information on tiger distributions (*ibid*). Conservation strategies for tigers had previously focused only on protecting the species in pristine wilderness areas and were based on the premise that estimates of tiger densities derived from sign-based indices (e.g., pugmark census techniques) were adequate to provide information on the survival status of the species. However, detecting tigers through traditional field survey methods is a challenging task. Tigers require sufficient numbers of large-bodied prey and therefore roam across large that may exceed 100s of kilometres. They also occur in low densities and often as lone individuals, particularly in closed forests (Gittleman and Harvey 1982; Carbone et al. 2001), are cryptic by nature and are rarely seen. As a consequence, records relating to tiger distributions and their use of habitats have been inadequate and this has severely impeded the formulation and implementation of appropriate conservation measures (Blake and Hedges 2004; Sanderson et al. 2006).

For these reasons, there has been an increasing and now urgent need to devise rapid yet rigorous population analysis and viability methods with spatial and temporal observations that are repeatable across the varied landscapes that tigers occupy (Linkie et al. 2006). It is also widely accepted that a landscape approach to tiger conservation that takes into account the distribution and condition of habitat also fares better than those that focus only on protecting the species. Although breeding populations are currently found in eight Asian range states, there are few regular empirical studies to indicate trends on a countrywide basis (Goodrich et al. 2015). Sanderson et al. (2006) put forward the concept of establishing Tiger Conservation Landscapes (TCLs) and estimating tiger populations across their entire range using multiple methods; from expert opinion to land cover (e.g., vegetation) and change assessments based on satellite sensor data. The study also highlighted that 76 TCLs held the major tiger subpopulations in the world. An additional 543 fragments were also identified, but they were considered too small to support long-term viable populations. 491 areas were designated as Tiger Survey Landscapes (TSL; total area of 1.1 million km²), where the current tiger status was unknown but the area was considered sufficiently large to support at least five tigers. The study highlighted that it

would be a major challenge to survey and monitor these TCLs on a regular basis unless new options for mapping and monitoring their state, condition and dynamics were developed and implemented.

Determining the Distribution and Abundance of Tigers

Whilst the ecology of wild tigers has been studied in depth (Sanderson et al. 2006), information on their present status is limited and scattered over a number of publications, with many in the grey literature. In a review conducted in support of this study, 35 papers were identified that provided information relating specifically to assessing tiger populations and their habitat, with these based largely on primary data collection. Approximately half of these studies used capture-recapture methods with a lesser proportion focusing on sign-based indices (such as tracks, visual estimates, scat DNA analysis; 25%), and satellite tracking (7%). Only one paper (Imam et al. 2009) explicitly used remote sensing data to assess tiger habitat suitability in the landscape. The review highlighted the general paucity of information, with only a few local-scale studies, but also the varied and often inconsistent approaches for estimating population distributions and sizes. Furthermore, many population estimates were found to be based on single-studies, typically field-based surveys, with these relying primarily on pugmark census, camera traps, satellite telemetry, scent-matching using dogs, fecal genetics and large scale occupancy surveys. Most studies also relied on capture-recapture techniques conducted over a specified period (Table 1).

From the 1970s to 2005, the pugmark census technique has been widely used and has relied on sign-based abundance estimates. The census is based on intensive monitoring of tigers within areas, identifying individual tigers by visual inspection of the pugmark tracings/plaster casts, measuring pug mark variables (e.g., for toe to pad distance, pad length and width etc.) and subsequently using statistical techniques to identify individuals and numbers (Choudhury 1970; Sharma et al. 2005).

Table 1 Advancement of methods for estimating tiger populations

| >1970 ^a | 1970 ^b | 1992–2005 ^c | 2005–2010 ^d | 2010-(proposed) |
|--|-------------------|---|--|--|
| Hunting and man-animal conflict records. | Pugmark census | Camera-traps, Prey-predator models, Landscape level habitat analysis. | Large-scale occupancy and Population modelling, faecal genetics and digital pugmarks | Integration of ground-based surveys and satellite-based observations |

^aRangarajan (2001)

^bChoudhary (1970), Karanth (1995)

^cWikramanayake et al. (1998), Mackenzie et al. (2002)

^dSharma et al. (2005), Carroll and Miquelle (2006), Sanderson et al. (2006), Samrat et al. (2009)

Satellite telemetry allows animals with radio collars to be tracked from the ground or air. Animal locations are plotted on base maps from which their home range can be approximated. This method is particularly useful for detecting the movement of individuals and understanding tiger ecology and behaviour (Smith et al. 1998).

Camera trapping has long been used to estimate populations of faunal species (Otis et al. 1978; Balme et al. 2009; Carbone et al. 2001; Harihar et al. 2009) and is currently the most accepted technique for studying tiger populations in the Indian Subcontinent (Karanth and Sunquist 1995; Karanth et al. 2002; Karanth et al. 2006; Royle et al. 2009; Wegge and Storaas 2009). This method works on the *a priori* premise that individual tigers have unique biometrics, such as stripe patterns or tail to body ratios, that can be captured by placing automated camera traps in optimal field locations. The biometric information can then be analyzed within a robust capture-recapture statistical framework to arrive at estimates of numbers. The technique has been used for determining the spatial location and movements of carnivores such as tigers (Karanth et al. 2006; O'Brian et al. 2003; Linkie et al. 2006), leopards (Harihar et al. 2011), pumas (Kelly et al. 2008), jaguars (Davis et al. 2010) and other large predators. New techniques that have been used in conjunction with camera traps include the use of scent-matching dogs for Amur tigers (Kerley and Salkina 2007), fecal genetics to prepare DNA profiles of individual tigers (Samrat et al. 2009) and large-scale occupancy surveys for tigers and their prey (Jhala et al. 2008).

Use of Remote Sensing Data for Tiger Habitat Mapping

To address the mapping of tigers distributions, a handful of studies (e.g., Sanderson et al. 2006; Imam et al. 2009) have used thematic or continuous layers (e.g., representing vegetation, land use and elevation data) derived from remote sensing data as input to Species Distribution Models (SDM) (e.g., occupancy) or population models. Most have focused on using freely available pre-processed optical satellite sensor data, pixel-based image classifications and geometry-based geospatial analysis (Karanth et al. 2009; Ranganathan et al. 2008; Jhala et al. 2008). However, their generation and use has often been compromised by uncertainty and errors (positional and thematic) related to geometric correction accuracy, poor atmospheric and topographic correction (particularly in the mountainous areas that tigers commonly occupy), and inconsistent use of classification and accuracy assessment techniques. There is, however, considerable interest in the use of remote sensing data, including as input to SDMs and population models, and the increased quality, diversity, availability and accessibility of data and derived products is contributing to greater uptake. A summary of information that can be obtained from remotely sensed data and which is relevant to understanding and/or modelling tiger distributions, movement and behaviour is provided in Table 2.

Table 2 Habitat suitability parameters that can be derived from satellite sensor data

| Factor | Relevance | Systems (Examples) |
|------------------------------|---|--|
| Elevation, slope, and aspect | Tigers prefer shallow to moderate slopes and, in winter, southerly facing aspects are often visited. | SRTM, ASTER, Tandem-X, PRISM |
| Water bodies | Water supply for tigers (primarily for drinking). | Optical, radar |
| Climate | Long term impacts on tiger distributions, movements and breeding. | TRMM ^a , MODIS ^b |
| Grassland productivity | Associated with fluctuations in ungulate numbers. During periods of low productivity, prey are often found close to water bodies | MODIS, Landsat, Sentinel-2 |
| Biomass | Easier movement for tigers within higher biomass forests because of greater openness of the ground layer. | ALOS PALSAR |
| Canopy height | Taller trees are typically associated with a more open understorey, which eases movement for tigers | ICESAT GLAS |
| Canopy cover | Tigers prefer vegetation with a higher percentage canopy cover | Optical |
| Settlements | Tigers avoid extensively urbanized areas but can occur near villages and isolated houses | SPOT-5, ASTER |
| Infrastructure | Roads limit the movement of tigers | High resolution data including Worldview and RapidEye |
| Logging roads | Indicate intrusion into the forest, which can restrict or limit tiger movements and occupation. | |
| Land cover | Tigers prefer areas of woody vegetation but will venture into grassland areas when hunting or moving between patches. | Optical and/or radar data |
| Land cover change | Losses and degradation of habitats occurs over time and the replacement habitats are often unsuitable. Regeneration of forests may favour movement of tigers through the landscape. | Time-series of optical and radar data |
| Fire history | Fire can initially disturb tigers but growth of ground vegetation can increase prey numbers and hence tigers | Fire hotspots mapped from MODIS and fire scars mapped from optical data. |

^aFor rainfall and ^bsnow cover

The Indo-Bhutan Manas Tiger Conservation Landscape (IBMTCL) and Its Conservation Significance

The IBMTCL lies at the critical juncture of the Indo-Malayan and the Indo-Gangetic bio-geographical pathways and has been lauded for its outstanding natural beauty and unparalleled diversity as a UNESCO World Heritage site (UNESCO 2008). The IBMTCL forms an important connecting link between the Buxa, Nameri and Pakke Tiger Reserves in India and the Hukaung Valley Tiger Reserve in Myanmar. Within

Table 3 PAs supporting tiger populations and methods for their estimation in IBMTCL

| Name of protected area | Area (km ²) | Forest type | Previous methods for estimating populations of tigers |
|-----------------------------------|-------------------------|---|---|
| Manas Tiger Reserve, India | 2837 | Subtropical forests interspersed with savannah grasslands | Camera trap studies undertaken since 2009 |
| Royal Manas National Park, Bhutan | 1057 | Subtropical forests | Camera trap studies undertaken since 2009 |
| Jigme Singye National Park | 1730 | Temperate and upland broadleaf forests | Single camera-trap study |
| Phibsoo Wildlife sanctuary | 269 | Subtropical landscapes | Not available |
| Khaling Wildlife Sanctuary | 335 | Subtropical | Not available |
| Bornadi Wildlife Sanctuary | 26 | Subtropical | Not available |
| TOTAL AREA | 6254 | | |

this region, a number of Park Areas (PAs) exist, including Jigme Singye National Park (NP), Royal Manas NP, Phibsoo Wildlife Sanctuary (WLS), Khaling WLS in Bhutan and the Manas Tiger Reserve (MTR) in India. Together, these form the single-largest TCL for tigers (*Panthera tigris tigris*) in the world (Dorji and Santiapillai 1989; Sanderson et al. 2006).

The IBMTCL is of historical evolutionary significance as tigers here share the connecting gene pool with the south eastern tiger population and the area represents the entry point of tigers into the Indian sub-continent (Jhala et al. 2011). Administratively, the IBMTCL is comprised of six Protected Areas (PAs; Table 3) but there are several potential landscapes which do not have PA status but nevertheless are able to support tigers (e.g., the Ripu-Chirang Forest complexes in India).

Data Collected

Mammal Surveys

Various organizations, including NGOs such as WWF-India, Aaranyak and the Wildlife Trust of India, assisted the Manas NP Authority in India to lay camera traps between November 2010 and February 2011. This was part of a nation-wide tiger sampling exercise carried out within most of the tiger reserves in India (Jhala et al. 2011). The infrared-triggered camera-traps used within the two ranges of Manas NP (Bansbari and Bhuyanpara) were the Cuddeback (Non Typical Inc. Wisconsin), TrailMaster (Goodson and Associates, Kansas, USA) and Panthera Camera Trap V3 (Panthera, USA). A pair of camera traps was placed within individual 2 × 2 km sized cells and the total area covered by all camera traps

approximated 300 km² (in India) (Table 4). In a separate but simultaneous exercise in Royal Manas NP, camera trapping was undertaken by the Department of Agriculture, Royal Government of Bhutan (RGoB) in collaboration with the Ugyen Wangchuk Institute for Conservation and Environment (UWICE) and the Bhutan Foundation, specifically to monitor the tiger population (Fig. 1). This study focused only on the camera trapping undertaken in Manas NP.

Table 4 Summary of camera trapping in IBMTCL

| | |
|---|--------------------------------|
| Total number of camera traps | 102 ^a |
| Sampling occasion | 64 days |
| Sampling effort (number of traps × sampling occasion) | 5955 |
| Camera trap polygon area | 436.37 km ² |
| Estimated buffer width (HMMDM) | 4.2 km |
| Effective sampled area | 789.2 (±50.98) km ² |

^a78 in or near the border of Manas NP

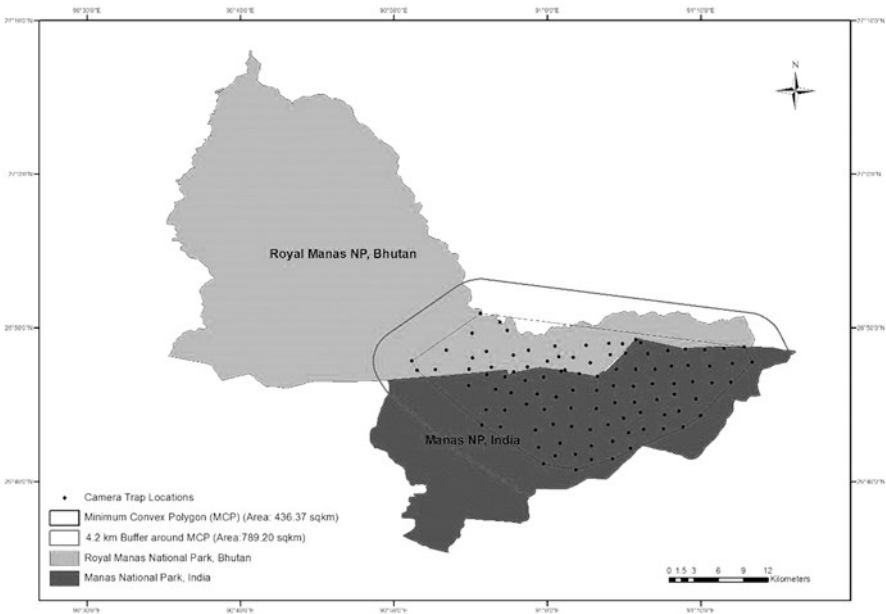


Fig. 1 The location of camera traps placed at IBMTCL between November 2010 and February 2011

Remote Sensing and Other Spatial Data

For the 21 and 30 January and 6 and 7 February 2010, relatively cloud free Landsat Enhanced Thematic Mapper (ETM+) data were downloaded from the Glovis (<http://glovis.usgs.gov/>) and Land Processes Distributed Active Archive Centre (https://lpdaac.usgs.gov/get_data/data_pool). These data were converted to surface reflectance (%) using the 6S atmospheric correction software. Radiometric normalization between scenes was also undertaken using the approach outlined by Homer et al. (1997). All images were geo-referenced by first establishing ground control points between locations identified from existing maps and the most cloud free Landsat sensor data, warping these images and then generating a mosaic covering the study area. Control points were then established subsequently between the remaining Landsat sensor data and this reference mosaic. The processing of the Landsat sensor data was undertaken using the open source software RSGISLib (www.rsgislib.org; Bunting et al. 2013).

The history of burning with the IBMTCL over the period 2000–2012 was documented by referencing the MODIS product MOD 14 (Thermal Anomalies – Fires and Biomass Burning). This product includes fire occurrence (day/night) and location, the logical criteria used for the fire selection and an energy calculation for each fire. 8-day and monthly day-and-night composite fire occurrence (full resolution) and gridded 10-km and 0.5° summaries (including counts) per fire class (daily/8-day/monthly) are also available. The Level 2 products include various fire related parameters including the occurrence of day and night time thermal anomalies, flagged and grouped into different temperature classes associated with different levels of emitted energy from the fire. These parameters are retrieved daily at 1 km spatial resolution.

An ASTER Global Digital Elevation Model (GDEM) was used (<http://asterweb.jpl.nasa.gov/gdem-wist.asp>) to establish the topography of the two national parks, with this released at 30 m resolution and available for 1 × 1 tiles (geographic projection). Other data layers were also available to support understanding the movement of large cats, including continuous distance from roads and the locations of anti-poaching camps and settlements. The park boundary, roads and rivers were digitized from topographic sheets and Google Earth images, although the boundary location was revised using the Landsat sensor data available for 2010.

Methods of Data Analysis

Analysis of Camera Trap Data

Each day (24 h) was defined as one sampling occasion (Otis et al. 1978) and this was repeated over a period of 57 days (Otis et al. 1978; Karanth 1995). Individual tigers were identified with reference to their documented stripe pattern, with this

undertaken by carefully examining the position and shape of stripes on the flanks, limbs, forequarters and sometimes the tail (Schaller 1967; Karanth and Nichols 1998). Each tiger captured in a photograph was then assigned a unique identification number (e.g. TM1M, TM2F for the first and second tiger of male and female gender). Similar procedures were undertaken for leopard and clouded leopard. Individual capture histories for tigers, leopards and clouded leopards were developed in a standard 'X-matrix format' (Otis et al. 1978) and these were analyzed using models developed for closed populations within the programs CAPTURE (Rexstad and Burnham 1991) and MARK (White 2008). The abundance of all three species for the effective sampled area was estimated by using a buffer around the locations, determined using half the mean of the maximum distance moved (HMMDM) model, and the area associated also with a trapping grid polygon (Karanth and Nichols 1998). A habitat mask was also used to remove non-tiger habitat (e.g., deep water, human settlements; Karanth and Nicols 2002). The density (per 100 km²) was then estimated by dividing this area by the population size (number of individuals). The density of individual prey species, which were also recorded through the camera traps, was estimated using the program DISTANCE (Thomas et al. 2010). This online software works by using detection functions that model the probability of detecting an animal given its distance from the transect. Further details of both methods can be found in Jhala et al. (2010).

Spatial Analysis of Field Data

The spatial configuration of home ranges of individual cats is an important property of their social systems and has been defined as an area traversed by individuals during normal activities of food gathering, mating and caring for young (Dillon and Kelly 2007). For this study, the GPS locations for each capture event and for identified individuals were extracted and plotted spatially. Where an animal was photographed, the distance from the camera trap was determined and a minimal-bounding polygon was constructed around each of the individual point locations where the same individual was sighted and also for all species of the same type. The resulting spatial datasets were then used to quantify ranging behavior, niche overlap and movement in relation to observed land cover types and landscape dynamics. Home range size is considered an important predictable aspect of an animal's feeding strategy and has been related to food density, metabolic needs and the efficiency of movement. The metric also indicates the degree of overlap as a function of territory and can reflect the variation in population and community characteristics. For example, home-range size is frequently correlated inversely with population density and home-range exclusiveness can indicate significant inter and intra-specific competition (*ibid*). To calculate the ranging patterns of tigers and sympatric carnivores within the habitat, a point density tool was used which calculates a magnitude per unit area from point features falling within a neighborhood around each cell. In addition, a minimum boundary geometry tool was used, which represents a

specified minimum bounding geometry enclosing each input feature for each group of input features.

Land Cover Classification

To classify land cover and associated changes between the different years, 150 training areas representing 14 land cover categories (see Table 5) were established, with a further 150 collected to subsequently assess the accuracy of the classification. A hybrid supervised classification of the Landsat ETM+ data (all spectral bands) was then undertaken within Erdas Imagine 9.3.

Table 5 Description of land cover types within the IBMTCL

| | LULC type | Description | Suitability for tigers |
|---|------------------------------------|--|--|
| 1 | Sub-tropical semi-evergreen forest | Occurs between 500 and 2000 m asl; dominated by a variety of trees and shrub species forming a multi-storey structure. The forests extend along the northern boundary of Manas NP and into Royal Manas NP, which has a wetter moisture regime and lower anthropogenic disturbance. | An ideal habitat for tigers, although supports lower densities of prey and predators |
| 2 | Temperate broadleaf forest | Occurs between 2000 and 2500 m asl; dominated by oak and laurel species although pine species are frequent in the inner dry valleys. Typical to Jigme Singye Dorji NP. | Tigers reported in Jigme Singye Wancgchuk NP. |
| 3 | Temperate conifer forest | Occurs between 2500 and 3000 m asl. Dominated mainly by conifer species (spruce and fir) and often has understory communities of deciduous broad-leaved and evergreen species (Wangda and Ohsawa 2006). Dominant forest type in the north of Jigme Singye Dorji NP. | Not suitable for tigers, although some reports of tigers present |
| 4 | Sub-alpine conifer forest | Occurs up to 4000 m asl. Dominated by cold-adapted and widespread conifer species such as spruce and juniper. | Not suitable for tigers, but other large predators (snow leopards) occur. |
| 5 | Alpine scrub | Occurs above 4000 m asl; the limit of tree growth and start of the alpine zone. Scattered shrubs (dwarf junipers and rhododendrons) can occur as high as 4932 m asl. | More suited to snow leopards |

(continued)

Table 5 (continued)

| | LULC type | Description | Suitability for tigers |
|----|-------------------------------------|---|---|
| 6 | Closed moist mixed deciduous forest | Occurs up to 700 m asl. Dominated by a single dipterocarp species (<i>Shorea robusta</i>) in drier areas. A mix of sub-tropical semi-evergreen tree species also occurs in the moister areas Canopy cover often exceeds 40%. Occurs along the Himalayan foothills and the northern boundary of the MTR. | Suitable for tigers. |
| 7 | Open moist mixed Deciduous forest | Occurs up to 700 m. The reduced canopy cover (to <40%) is, in part, the result of selective removal of dipterocarp and other timber species. Dominates much of the MTR buffer. | Not suitable for tigers as highly fragmented and disturbed disturbance. |
| 8 | Alluvial short grasslands | Occurs up to 200 m. Soil-climax habitat type dominated by annual grass species that occur over seasonal wetlands. Now confined to patches within Manas NP and highly regulated by fires and annual flooding. | Highly suitable for prey and supports one of the highest densities of tigers in the world (Ahmed et al. 2010). 4.5% of the total habitat in Manas NP. |
| 9 | Savannah tall grasslands | Occurs up to 200 m. Soil-climax habitat type dominated by perennial grass species interspersed with colonizing tree species (characteristic of savannahs). Highly regulated by forest fires and flooding with patchy distribution within Manas NP. | Highly suitable for prey with very high densities of tigers (similar to class 8; Ahmed et al. 2010). 10% of the total habitat in Manas NP. |
| 10 | Riverine/sandy vegetation | Occur along the fringe of rivers that are characterized by sand and boulders (largely debris carried downstream by Himalayan streams); colonized by lichens and grasses. | Suitable for a range of prey and large cats as adjacent to water sources. |
| 11 | Waterbody | All major and minor rivers; typically narrow and fast flowing in the upper reaches but less water in the middle stream area; seasonal flow regulated by rainfall and silt load is variable. | Essential for all wild animals as the primary source of natural water. |
| 12 | Cultivation | All non-forest areas that are cultivated (primarily for paddy) during the monsoon season. | Not suitable for tigers. |
| 13 | Plantation | Monoculture plantation of tea bushes interspersed with deciduous tree species. Some tea gardens declared as forest reserves. Rubber is the main plantation crop and is typically managed by private growers. Plantation developments often lead to forest encroachment and fragmentation. | Not suitable for tigers. |
| 14 | Snow | Only in the higher elevations of Bhutan. | Not applicable |

Carnivore Distribution in Relation to Anthropogenic Disturbance

Fires, roads and settlements were considered to be the main anthropogenic disturbances likely to influence the distribution and movement of large cats within the landscape. The point distances tool available in the ArcGIS Geospatial Modelling Environment (GSM; <http://www.spatial ecology.com/gme> and previously known as Hawth's tools) was used to calculate the distances from tiger observations to fire locations over the observation period. This tool, which was designed to produce flexible distance matrix outputs, calculates distances between points. The output of distance between each fire location and species capture point was then categorized into 500 m intervals and analyzed using simple regression analysis. The null hypothesis that there was no link between fire and carnivore occurrence was rejected where $p > 0.05$.

Results

Camera Trap Sightings

A total of 14 tigers (8 males and 6 females) were identified from the camera trap photographs (Table 6, Fig. 2). Other top carnivores sighted during the same survey period included 27 leopards (*Panthera pardus*; 11 males, 13 females, 3 unidentified) and 16 clouded leopards (*Neofelis nebulosa*; 4 males, 5 females, 7 unidentified) (Fig. 3). Others species that were photographed included the marbled cat (*Pardofelis marmorata*), Leopard Cat (*Prionailurus bengalensis*), Jungle Cat (*Felis chaus*), Dhole (*Cuon alpinus*), Himalayan Black Bear (*Ursus thibetanus*), Sloth Bear (*Melursus ursinus*), Jackal (*Canis aureus*) and Civet species. Herbivore prey species photo captured included gaur (*Bos gaurus*), wild pig (*Sus scrofa*), sambar (*Rusa unicolor*), hog deer (*Hyelaphus porcinus*) and barking deer (*Muntiacus muntjac*) (Borah et al. 2012).

Table 6 Camera trap sightings of tigers

| | |
|--|---|
| Number of individual tigers captured | 14 |
| Estimated numbers of tigers in the sample area using model Mb | 15 (95% CI: 15–29) |
| Estimated tiger density in sampled area using HMMDM ^a | 1.9 (± 0.36) tigers 100 km ⁻² |
| Estimated tiger density using MLSECR ^b | 0.75 (± 0.21) tigers 100 km ⁻² |

^aHalf Mean Maximum Distance Moved

^bMaximum Likelihood Spatially explicit Capture Recapture based on Half normal method

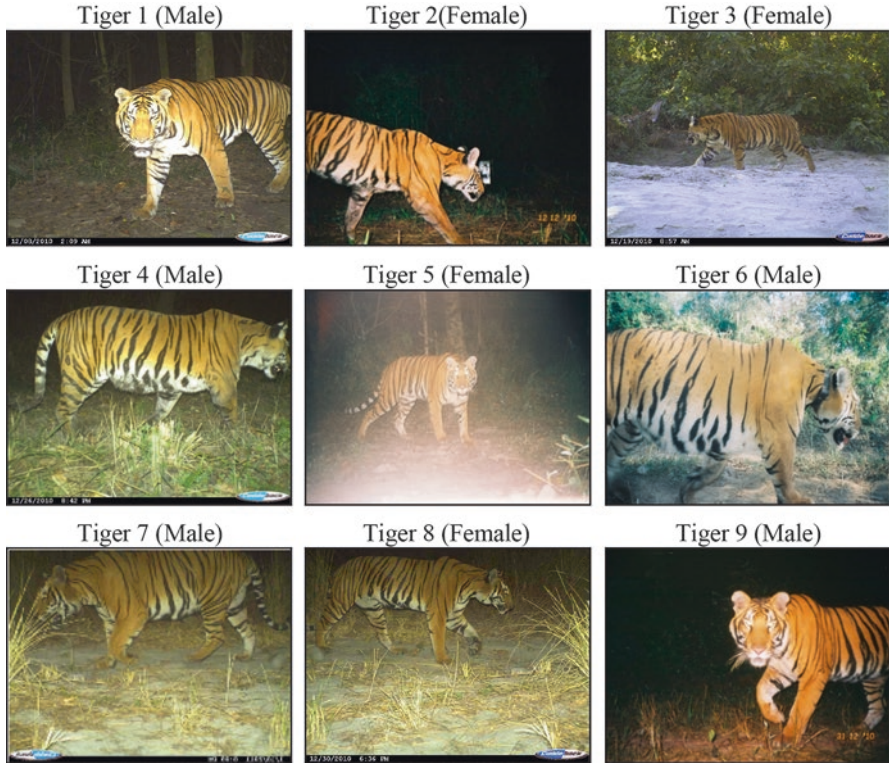


Fig. 2 Camera trap pictures of individual tigers in the IBMTCL (Nov 2010–Feb 2011; Source: Forest Department, Manas and Borah et al. 2012)

Ranging Pattern and Seasonal Home Range

Within Manas NP, tigers were found to be highly territorial (Fig. 2), with males sharing their territory with only 1 or 2 females. However, one adult male tiger (Tiger 1; and possibly the dominant) shared its territory with almost all the other individuals. The range of one female was significantly greater than that of others (Table 7), which may be attributed to the sub-optimal habitats in her territory. During the observation period, all tigers were moving to the areas of higher elevation to the north (i.e., towards Bhutan). No tigers were observed near the boundary of Manas NP, with most occurring towards the central area.

Leopards and Clouded Leopards shared much of their territory with tigers, although their movement was more restricted to the fringe areas. This also corroborates with studies elsewhere (e.g., Harihar et al. 2011) that sympatric species of carnivores co-exist in sub-optimal habitats (Fig. 4).

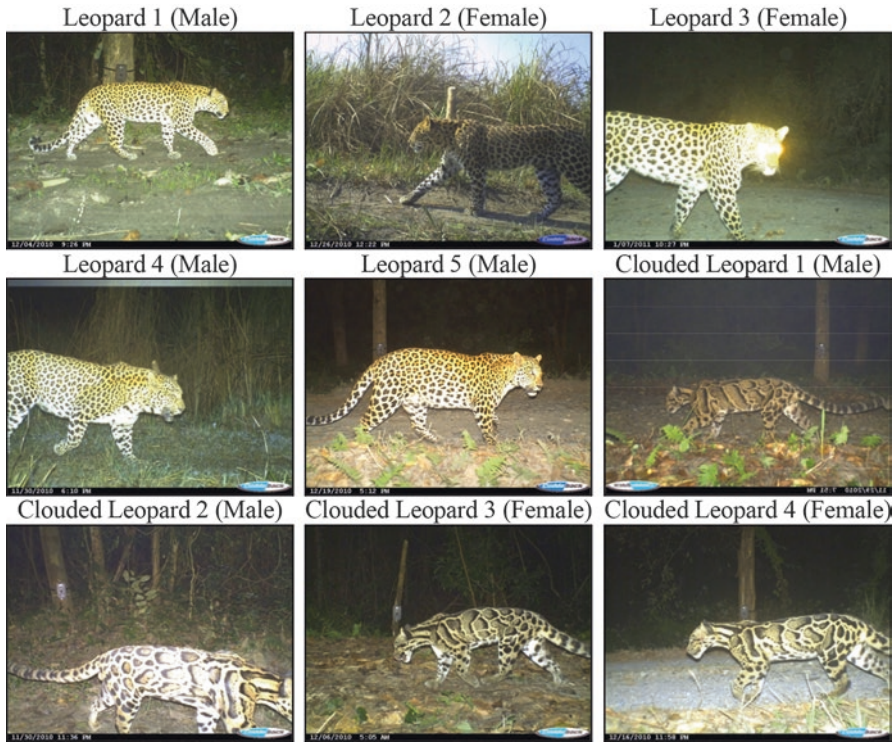


Fig. 3 Camera trap pictures of some Leopards and Clouded Leopards in the IBMTCL (Nov 2010–Feb 2011; Source: Forest Department, Manas and Borah et al. 2012)

Table 7 Summary of the dispersal of tigers in Manas NP (Nov 2010–Feb 2011)

| ID | Sex | DOFC | DOLC | No of traps captured | Ranging pattern (km ²) | Area of overlap (km ²) |
|---------|--------|--------|--------|----------------------|------------------------------------|------------------------------------|
| Tiger 1 | Male | 27 Nov | 19 Jan | 28 | 232 | |
| Tiger 2 | Female | 27 Nov | 28 Dec | 4 | 14 | Tiger 1 (5.9) |
| Tiger 3 | Female | 17 Dec | 19 Dec | 2 | – | |
| Tiger 4 | Female | 14 Dec | 16 Jan | 9 | 91 | Tiger 1 (85.4) |
| Tiger 5 | Female | 31 Dec | 1 Jan | 2 | – | |
| Tiger 6 | Male | 12 Dec | 8 Jan | 2 | – | |
| Tiger 7 | Male | 18 Jan | 18 Jan | 1 | – | |
| Tiger 8 | Female | 12 Jan | 30 Jan | 2 | – | |
| Tiger 9 | Male | 31 Dec | 19 Jan | 2 | – | |

DOFC Date of First Capture, DOLC Date of Last Capture

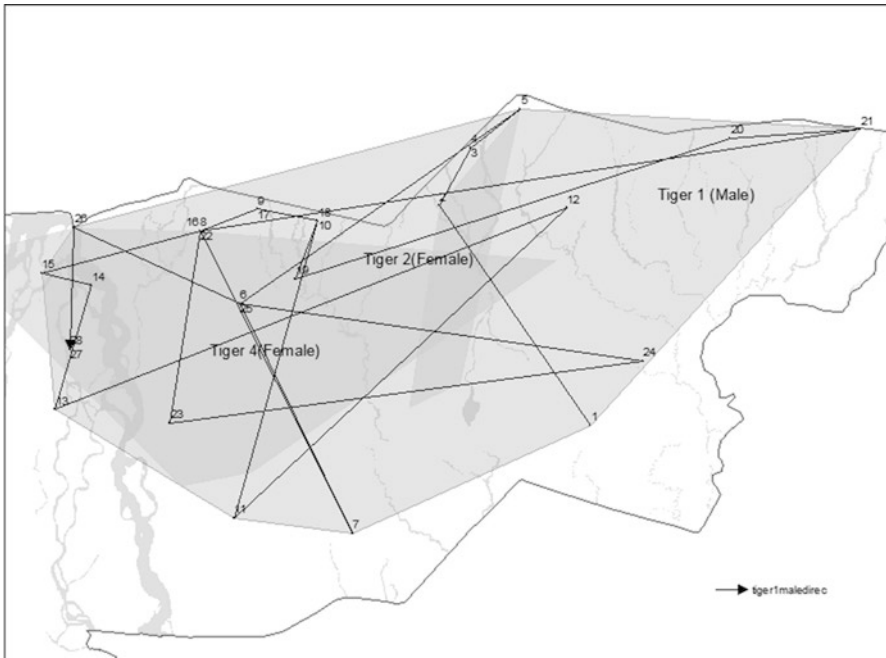


Fig. 4 Ranging pattern of female tigers in relation to the movement of the dominant male v(Tiger 1) in IBMTCL (Camera trap Area = 300 km²)

Land Cover Classifications and Carnivore Preferences

The classification of land covers for the IBMTCL is illustrated in Fig. 5. The majority of the lowland was occupied by closed moist mixed deciduous forests, with subtropical evergreen forest dominating the lower slopes and progressing into temperate broadleaved and coniferous forests and then subalpine vegetation with increasing elevation. Grasslands were found primarily in the south of the IBMTCL and riverine vegetation and unconsolidated deposits occurred along the wide river channels. Based on standard confusion matrices, the overall accuracy in the classification of land covers was 81.5% (kappa coefficient of 0.78), with the majority of users' or producers' accuracies exceeding 80% but being as low as 40% for some classes (e.g., user's accuracy 60% for cultivation and scrub, 56.7% for closed moist mixed forests). Manas NP supported many of the habitats suitable for tigers including the moist mixed deciduous forests (36.5%), semi-evergreen forest (19.1%), riverine sandy areas (15.1%) and moist alluvial grassland (8.4%). During the observation period, female tigers were most commonly recorded in the closed moist deciduous forests, whereas males were also recorded in sandy riverine areas close to forests. Although considered suitable because of the large numbers of prey, both sexes were not recorded within the tall savanna grasslands but rather remained on the periphery. Leopards and clouded leopards were observed primarily in the riverine areas.

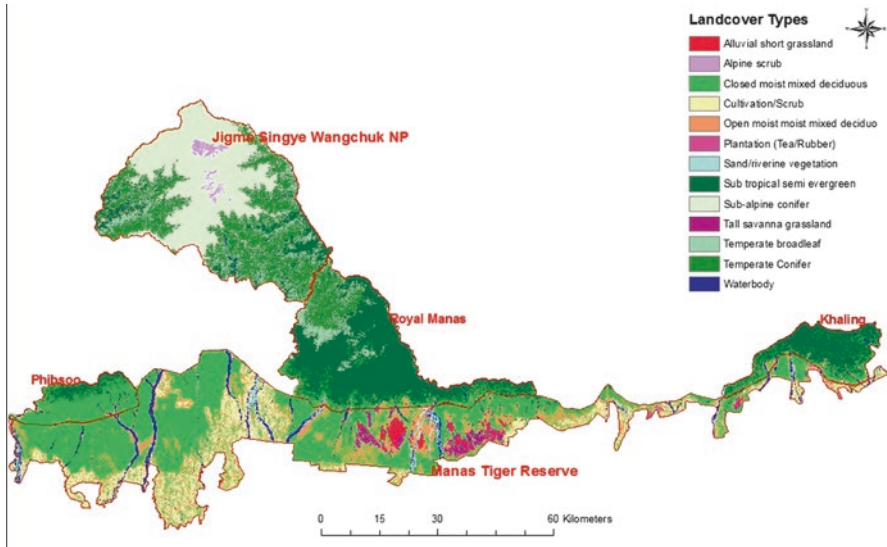


Fig. 5 Land cover classification of the IBMTCL generated from 2010 Landsat TM data

Distributions of Tigers in Relation to Fires and Anthropogenic Disturbance

The Manas NP section of the IBMTCL landscape experienced repeated and extensive burning between 2000 and 2012, with 1749 fire events recorded in the MOD 14 product. The greatest number of fires was in 2011, with 271 recorded (Fig. 6a). In all years, there was considerable intra-annual variability, with the period December to March associated with the highest frequency of fires. The transition period before and after the monsoon season (May to September) (i.e., the first and last 2 months of the dry season) experienced fewer fires. Manas NP is divided into three ranges; the western range (Panbari), central (Bansbari) and eastern (Bhuyanpara), and the density of fires (5.13 km^{-2}) was greatest in the grassland areas of the Bansbari range, with those in the Kuribeel and Pahu field areas repeatedly burnt. The incidence of fires was greatest in the more open moist mixed deciduous forests (Fig. 6b; Table 8), with this attributed largely to human activities. Over the period of the camera trapping, 32 fires were detected in the areas within which camera traps were placed. Reference to the tiger data indicated that the highest number of counts (indicating presence) was at a distance of 5–10 km from fires and often around the margins of burnt areas (Fig. 7). In general, tigers were recorded away from roads and village settlements, with this indicating their sensitivity to human activity, including vehicular movements.

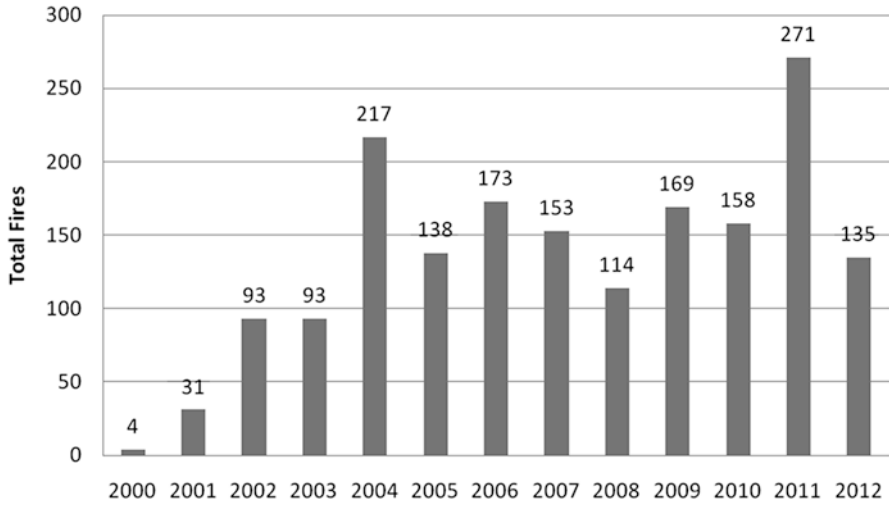


Fig. 6 The frequency of fires in the IBMTCL between 2000 and 2012 as determined from MODIS data

Table 8 Summary of fire distribution in land-cover types in Manas NP, India

| Forest type | Area (km ²) | Area (%) | Total Fires | (%) | Fires # km ⁻² |
|------------------------------|-------------------------|----------|-------------|-----|--------------------------|
| Semi evergreen forest | 104.1 | 19.1 | 112 | 6 | 1.08 |
| Riverine/sandy areas | 82.1 | 15.1 | 321 | 18 | 3.91 |
| Moist mixed deciduous forest | 197.9 | 36.5 | 569 | 33 | 2.88 |
| Moist alluvial grassland | 45.6 | 8.4 | 434 | 25 | 9.51 |
| Degraded/scrub Forest | 35.8 | 6.6 | 173 | 10 | 4.83 |
| Tall savannah grassland | 77.3 | 14.3 | 140 | 8 | 1.81 |
| TOTAL | 542.8 | 100.00 | 1749 | | |

Discussion

The Role of Earth Observation

The main benefit of using earth observation data was the ability to provide a land cover classification for a similar period as the camera trap surveys. The overall accuracy of the land cover classification for the IBMTCL was relatively high, but there was confusion between a number of classes, largely because of the high seasonal variation in the phenology of vegetation but also fires and flooding. In some areas, dry areas became inundated during the wet season, but as the waters receded, extensive areas of highly productive grassland established. These became senescent as the dry season progressed and many were then subject to extensive burning. Hence, the spectral signatures of the same area of ground varied considerably

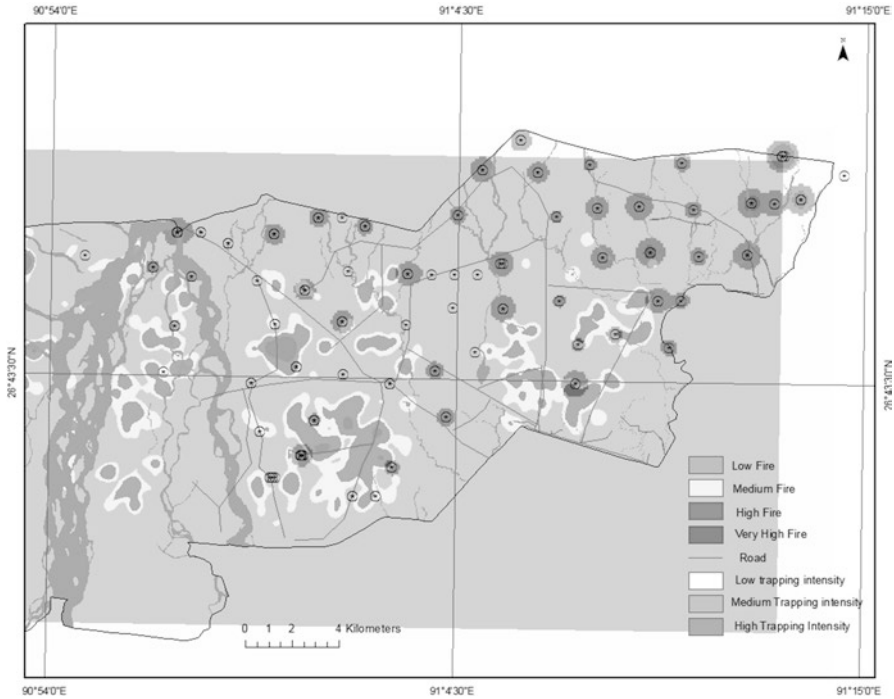


Fig. 7 The distribution of tiger observations in relation to fire density in the Manas NP section of the IBMTCL

(senescent and productive grassland, water and burnt ground). For this reason, the use of dense time-series of optical remote sensing data would provide a better overview of the changing states of vegetated and non-vegetated environments within the IBMTCL. Whilst atmospheric correction of the Landsat sensor data was undertaken, smoke haze and cloud still limited reliable retrieval of surface reflectance for some areas.

A further limitation of the land cover maps was that insufficient information on the structural characteristics of forests that might influence tiger movements was obtained, particularly in relation to the tree canopy density and canopy height. A common approach to estimating canopy cover is to establish relationships between ground based measurements and combinations of reflectance data. However, the lack of ground data and seasonal changes in leaf cover prevented the generation of reliable retrieval algorithms or use of those that are existing. Information on canopy height was also not obtained although there is potential to retrieve this using NASA's Ice, Cloud, and land Elevation (ICESat) satellite Geoscience Laser Altimeter System (GLAS). Future mapping could therefore focus on developing these products and applying classification schemes that consider their inclusion such as the Food and Agricultural Organisation's (FAO) Land Cover Classification System (LCCS; see

Lucas and Mitchell (2017; this book). The MODIS data provided invaluable insights into the frequency and distribution of fires, identifying that the majority occurred in the moist mixed deciduous forests and alluvial grasslands.

Distribution and Movement of Tigers

Although camera trapping occurred over a relatively short period, 52 tiger sightings were obtained. The resulting photographs allowed 14 different individuals to be distinguished and their gender determined. The movement of tigers was variable but several individuals moved large distances (tens of kilometers), with one male having a substantive range (232 km²). A general movement of tigers towards forested areas in the northern sections (of slightly higher elevation) may be attributable to the comparatively low availability of prey in the grassland areas during the winter months.

Reference to the land cover classification generated from Landsat sensor data indicated that the majority of tigers remained within the forest areas, although some males ventured into the riverine areas. Whilst recognizing that the observation period was relatively short, it was evident that some tigers remained in forest areas in proximity to the fires but were also sufficiently far away (typically 5–10 km) from the last known burn. It is hypothesized that tigers may stay close to areas that are burning (or may be susceptible to burning) in order to take advantage of prey species fleeing from the fire. They may also anticipate or take advantage of the prey species returning to graze on new growth in the periods following the fires. The influence of fires on the distribution of large cats and their prey has also been noted by Sarma et al. (2008) and Takahata et al. (2010) but further studies are needed to specifically link occurrence and movements with fire activity. Avoidance of areas occupied or influenced by humans was noticeable, with many individuals located towards the less disturbed central areas where human activity and vehicular movements were minimal and prey was more abundant.

A practical outcome from the study is that information generated on individual movement of tigers can assist future surveillance, especially as the likelihood of tiger movements can be communicated to the forest camps. Training in the use of camera traps and photographic interpretation allows frontline staff to identify individual tigers and contribute to a better understanding of their ranging behaviour in this landscape. Whilst tigers may benefit from fires, they may also be disturbed from those that are human-induced and therefore the establishment of camps in close proximity to fire prone areas may lead to prevention of many and hence less overall disturbance of habitats.

The tigers showed minimal overlap with leopards and clouded leopards and some studies (e.g., Rabinowitz et al. 1987) have suggested that the clouded leopard may alter its range or become less nocturnal when larger competitive species occur. Further research on the movement of tigers and other large cats based on camera

trap surveys is nevertheless advocated in order to better determine their interactions and the distribution of their prey. The camera traps also provide a basis for better estimating the abundance and density of large cats and to therefore monitor changes and trends in populations and their behaviour.

When used in combination with camera trapping and other monitoring techniques, earth observation data can play a role in understanding how large carnivores utilize the IBMTCL during different times of the year. These data can also be used to address connectivity issues within and between landscapes. Several new initiatives have included the development of software (e.g., MIST, SMART, M-STripES) that facilitate spatial monitoring of tiger populations including through the integration of field observations. Within such systems, there is considerable opportunity to make better use of the large, extensive and publically available archives of satellite sensor data.

Final Conclusions

In 1998, the global tiger population was estimated at 5000–7000 individuals (Seidensticker and McDougal 1993). By 2014, however, the global tiger population was at an historic low of approximately 3500 individuals, having declined by more than 50% of what they were just a few decades earlier (Goodrich et al. 2015). Given this situation, there is an urgent need to prioritize efforts to protect the remaining tiger populations (Stokes 2010; Walston et al. 2010). For the most part, these are found in PAs (Chapron et al. 2008; Rabinowitz 2009; Clements et al. 2010; Walston et al. 2010) but there are considerable opportunities to expand their range, including by connecting areas where they occur. This study has highlighted the potential of using earth observation data in conjunction with ground-based (including camera trap) surveys for better understanding the distribution, movement and preferences of tigers and a recommendation is to develop what is termed a Tiger Observation System (TOS) to maximize these opportunities. Whereas past use of earth observation data has been limited by availability and cost, the release of the Landsat sensor archive and the provision of freely available Sentinel-1 and -2 radar and optical sensor data respectively gives tiger conservation efforts additional impetus to achieve their long term conservation and expansion of populations.

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