Identifying spatial and temporal patterns of fire in the Manas National Park, India: Implications for grassland habitat conservation

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Abstract

Under increasing pressures from rapid human population growth, grasslands in tropical regions have been very modified by humans for centuries. As a consequence, tall grasslands in the Himalayan foothills are a highly threatened ecosystem containing unique and diverse plant assemblages and globally endangered large charismatic species, such as tigers, greater one-honed rhinoceros, and smaller creatures like hispid hares and pygmy hogs.

Fire management is a major issue for these grasslands in protected areas (PAs) in the Terai region, but information about grassland burning is still limited. In this study I first overviewed advanced research and some trials in other parts of the world. In relevant studies consulted, experts have measured the impact of fire on biodiversity. To deal with its complexity, conservation managers worldwide have preferred patchy mosaic burning. However, it is more suitable in the MNP to set up unburnt areas because some endangered species there are recognized as being fire-sensitive.

I analyzed spatial and temporal patterns of fires in the Manas National Park (MNP), India using remote sensing data, MODIS active fire products, recorded during 8 dry-seasons from 2000 to 2008. The correlation between fire frequency and 4 land-cover types was investigated, and effect of distance of fires to roads, rivers and park boundary was estimated using a generalized linear model (GLM). Burning intensity by areas was analyzed using a kernel density estimation tool within a GIS. This showed that 85% of total fires occurred between December and March, over half in grasslands (53.3%). The highest fire density was detected in wetlands, and there was a significant correlation between fire occurrence and distance from rivers. Three distinct intensively burnt areas were identified that corresponded with grasslands and wetlands in the MNP.

According to these results and the literature review, I make five main recommendations for effective management in the MNP: 1) targeting fire-sensitive species; 2) setting spatially and temporally unburnt areas; 3) regular fire records to build up baseline data; 4) examinations to detect the impact of grassland burning in the three intensive areas; 5) further study of relations between fire and fluvial influences.

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1. Introduction

The Terai is a belt of marshy grasslands, savannas, and forests at the base of the Himalaya range in India, Nepal, and Bhutan, from the Yamuna River in the west to the Brahmaputra River in the east. Within the Terai region, tall grasslands form a unique landscape of importance to biodiversity within the Indian subcontinent. Tall grasslands are found along the huge flood plains of two great rivers, the Ganges and Brahmaputra, associated with thousands of streams from Himalaya (Valkenburg 1934).

The Himalaya foothills are essentially linked to two significant geographical features: the presence of the world's youngest and tallest mountain range, Himalaya, and a dominant annual climatic event, the Asian monsoon. The latter brings very high rainfall to the southern foothills of the Himalaya and Teral lowlands. As a result, the region has one of the world's highest precipitations; it also divides the year into a very distinct dry and wet season.

As a consequence of the highly dynamic geology and climate, tall grasslands in this region have been maintained as climax vegetation by fluvial influences such as changing river courses, long periods of inundation and the amounts of alluvial deposits. According to Peet et al. (2002), Terai grasslands represent highly diverse plants associated with nine assemblages and eight successional phases. With changes of river courses and flood areas, plant communities are occasionally wiped out, and different plant assemblages emerge depending on successional stages (Peet et al. 2002). These grasslands are among the tallest in the world, and are maintained by silt deposited by the yearly monsoon floods. Important grasses include Kans grass (*Saccharum spontaneum*) and Baruwa grass (*Saccharum benghalensis*).

Terai grasslands are also important for many animal species including nationally or globally threatened species such as tigers (*Panthera tigris*), Asian elephant (*Elephas maximus*), greater one-horned rhinoceros (*Rhinoceros unicornis*), and swamp deer (*Cervus duvauceli*). Medium-sized mammals, the hispid hares (*Caprolagus hispidus*) and pygmy hogs (*Sus salvanius*) are restricted to tall grasslands (Oliver 1981, Bell & Oliver 1992, Narayan et al. in press).

Despite their uniqueness and biological importance, tall grasslands in the Indian subcontinent are a highly threatened ecosystem. Currently, only about 2% of the original tall grasslands remain, often severely fragmented and mostly confined to protected areas (PAs) (Narayan et al. in press). Much of the tall grasslands has been converted to farmland and has led to the disappearance of much of the biodiversity in the region, and most threatened species now survive within PAs.

The major threats to tall grasslands result from human activities, especially landscape transformation (Hoeskstra et al. 2005). The underlying driver of these threats is the unprecedented rapid human population growth throughout southern Nepal and northern India. For example, the Indian population is projected to be around 1.4 billion in 2025, concentrated in northern India with 35% of the current population in Assam, 51% in Bihar and 55% in Utter Pradesh (Dyson et al. 2004). The Terai grasslands are found within these regions. To support such a massive population across these regions, tall grasslands have been converted into economically profitable lands for infrastructure, settlement and agriculture use.

Threats such as frequent burning, heavy grazing, harvesting grass and modification of river channels still continue to affect the severely fragmented ecosystems (Mathur 1999). In particular, anthropogenic fires are thought be one of the major drivers of change in tall grasslands. Even in PAs, burning occurs in order for local villagers to enlarge grazing lands, or by park rangers as a management tool.

Fire management is a major issue for Terai grassland conservation for both uncontrolled and prescribed burning. A better understanding of the role of fire within this ecosystem is essential. However, existing knowledge about the occurrence and impact of fires is limited and usually derived from anecdotal information or observational reports (Ghosh 1997).

Moreover, there is still a limited amount of data demonstrating which fire regimes benefit the ecosystem and which would damage it (Peet et al. 1997). Quantitative information derived from experimental research required (Anderson et al. 2005) is difficult to often in dispersed patches in seriously fragmented landscape led by rapid human occupation. On the other hand, fire studies are supposed to confirm how a management goal could be met (Parr & Chown. 2003). Current developments in remote sensing technology and geographic information systems (GIS) permit more sophisticated investigations of spatial and temporal patterns of fire presence and derive some understanding of occurrence in selected areas (Franca & Setzer 1999, Eva & Lambin 1997, Laris 2002). Furthermore, some management requirements suggested by advanced research in other tropical regions (Oregeas & Andersen 2001, Andersen 2004, Parr & Chown 2003, Parr et al. 2006,) are useful for consideration of fire management in PAs holding threatened Terai grassland ecosystem. For example, strategic fire management was established after long-term fire records in the Kruger National Park in South Africa (Biggs 2002) and assessments of the impact of grassland burning on biodiversity in the wet tropical region in Southern Australia (Parr & Chown 2003).

The objective of this project is to investigate spatial and temporal patterns of fire in the Manas National Park (MNP), Assam, India using Geographical Information Systems (GIS) and Remote Sensing. The information gathered by this project can be used by the Assamese Forestry Department to manage and conserve the fire prone areas more efficiently. The forecasting and prevention of more expansion of fires also benefits the local communities residing in and around PAs whose livelihood depends on the natural resources.

Firstly, I present here an overview of the impacts of fire on biodiversity, and information on trials for fire management undertaken in different parts of the world. From this literature review, I extracted key factors that are applicable to PAs in northern India. Secondly, using satellite data gathered on fire occurrences for the past nine years, I analyze the frequency of fire occurrences and map their distribution throughout the MNP. Finally, I discuss the way in which fire management can be improved in the MNP, especially in relation to tall grasslands.

2. Literature Review

The purpose of the literature review here is to obtain useful information and current knowledge that are applicable to tall grassland conservation in northern India. It reviewed 1) updated findings about fire impacts on biodiversity from research in other tropical fire-prone regions; 2) existing knowledge about fire impacts on the tall grasslands and its biodiversity within the study regions; 3) changing fire policy and management in general; 4) conservation and management issues in tall grasslands in the northern Indian; 5) and finally, key components for the establishment of effective fire management extracted from relatively well-studied areas in the world.

2.1. Fire impacts on biodiversity in other tropical fire-prone regions

First of all, perceptions of fire have been clearly linked to ecosystem principles, and have changed with shifting ecological paradigms (Parr & Chown 2003). Until the early 1980s, fire was thought be a detrimental agent to the balance-of-nature based on equilibrium theory. Since the establishment of a new vision of ecological systems as having more dynamic and complex processes, fire has been regarded as an important factor to promote ecological dynamics rather than as a negative disturbance to the stable balance of nature. In particular, tropical and sub-tropical savannas are acknowledged as more resilient ecosystems than people expected, according to substantial research in Australia and Africa (Orgeous & Andersen 2001, Andersen el.at. 2005, Smith et al. 2005).

Understanding the impacts of fire on biodiversity is mandatory for conservation. It has become accepted that fire has a considerable influence on all ecosystems, but a single fire never affects only one species in a simple way. Historically, early discoveries of positive fire impacts were described by forestry scientists; for example, some economically important tree species such as teaks in South-east Asia or eucalypt species in Australia germinate only after a fire event (Rakyutitham 2001, Spencer & Baxter 2006,). Some intensive experimental researches have investigated how fires change plant communities and their structure. For example, the structure of eucalypt forest varies in different fire frequencies (Spencer &

Baxter 2006, Fenner & Bull 2007). Also, in an African savanna, the height and abundance of scattered trees in the grassland were determined by fire severity (Govender et al. 2006). In many cases in tropical savannas, long-term fire exclusion promotes succession to a more woody landscape.

In order to develop more effective management for forestry or farming, fire research has focused more on economically important vegetation changes rather than on wild flora and fauna species (Bladstock el at. 2002). Therefore, there has been an assumption among fire researchers that heterogeneity of vegetation could likely be a surrogate of biodiversity (Brockett et al. 2001). However in some current studies, responses to fire were not simple in different group of species to different types of fire. For example, some plants have fire-dependent characteristics while others have a fire-sensitive response (Spencer & Baxter 2006). In a fire-prone ecosystem like a tropical savanna, many species have evolved to adapt to wildfire occurring during the dry-season. Although many grass-layer arthropod species show resilience to fire in the short term, the accumulated influence of frequent burning for a long period is still unknown, and poorly mobile species such as spiders are more likely to be vulnerable (Andersen et al. 2004). Some hole-dwelling lizards have the capability to survive during fire, but even if their survival and reproductive rates remain stable, their behavioural change leads to a serious reduction in their body condition that increases mortality in the post-fire period (Fenner & Bull 2007). Even with high mobility, certain avian species are susceptible to fire damage during the breeding season, especially ground-nesting birds (Inskipp & Inskipp 1983). After a long interval between grassland fires, the diversity of bird species is known to decrease; in contrast, rapid new growth and seeds emerge soon after burning to give ephemeral benefits to agile bird species (Bowman et al. 1998). At the same time, a flush of new growth is also very attractive to large herbivores due to its supremely rich nutrients. Grassland burning techniques to benefit grazing lands have been well-developed for economic purposes, and suggest that the use of fire is beneficial for the conservation of endangered large herbivores (Fuhlendorf & Engle 2004).

In contrast to large mammals, data on the effects of fire on small mammals are confined to only a few individual species. A study of small mammals in Kapaly, Australia, indicates a high vulnerability of rodents to fire. Here six of seven common species were more significantly abundant in unburnt areas than in burnt patches (Corbett et al. 2003). In this study, intensive and widespread fires increased the direct mortality of small mammals significantly. Moreover, greater exposure to predators and a shortage of food resources after a fire might decrease the survival of small mammal species (Griffiths & Christian 1996, Pardon et al. 2003). Generally, grasslands are a suitable habitat for such small mammals since they protect them from predation and poaching, particularly in a situation where grasslands are already highly fragmented. Although much more work needs to be done, the data available shows significant negative impacts from grassland burning on small mammal species, more than on other taxa. Therefore, it should be noted that setting aside unburnt areas is essential to these fire-sensitive species to prevent further population reduction.

Fig. 1. A short grassland opening in the Manas National Park.

Photo by Goutam Narayan (Durrell / EcoSystems-India)

2.2. Impacts of fire on biodiversity of tall grasslands in Indian subcontinent

Despite fire being one of the major factors to affect habitat quality of the Terai grasslands, the impacts on vegetation and a series of endangered species are poorly known (Lehmkuhl 1989, Peet et al. 1997). Basically, the grasslands are located on the floodplain, affected by river dynamics with seasonal changes in rainfall, so the ecosystem is never stable. Consequently, the influence of fire on plant communities is complicated within their different successional stages corresponding with other environmental factors such as annual rainfall, a period of inundation, and cutting and grazing.

According to comprehensive research in Nepal by Peet et al. (1997), graminoid plants represented resilience to recolonization after fire treatment, and the richness of plant species was slightly higher than in unburnt areas. With clarified classification in Terai grassland plant assemblages, experts stress the importance of the *Imperata cylindrica* assemblage as a critical habitat in conservation because of its vulnerability. This assemblage appears in ephemeral conditions with relatively drier locations in marginalized areas away from flooding (Fig.1). These areas are very suitable for human land use as settlements or farming as well as for wildlife survival. Furthermore, without any disturbance *I. cylindrica* dominated vegetation easily shifts to wooded land, so burning and cutting are necessary to maintain the grassland because of the absence of fluvial impacts (Dabadghao and Shankarnarayan 1973).

Animals do not utilize grassland in the same ways, with different demands from individual species, so it is clear that the effects of fire are not felt equally positively or negatively among various taxa. Some large herbivores, swamp deer, chital, wild buffalo and domestic stocks could have benefits for foraging on nutrient-rich new grass on occasionally emerged open lands after a fire event (Peet et al. 1997). On the other hand, some smaller herbivores such as hog deer prefer much denser grasslands to avoid predation. While open post-fire lands give advantages to some herbivores, the loss of inaccessible tall grassland causes newborn calves of deer and rhinos to be much more vulnerable to hunting by carnivores, but other research suggests tigers also need cover for successful hunting (Sunguist 1981). In terms of conservation, impacts on fire-sensitive species should be firstly be considered for small mammals, ground nesting birds and other slow moving animals, such as reptiles and amphibians. There is a lack of data on the impact of fire on herpetofauna in Terai grassland habitats in the Indian sub-continent. While large numbers of Indian endemic species are recorded in inventories, they are rapidly disappearing in some areas where frequent fires occur (Chatterjee et al. 2006). For ground breeding birds, for instance the globally endangered Bengal Florican, burning in the late dry-season is detrimental for their chick's survival (Inskipp & Inskipp 1983)

Finally, the influence of grass burning on small mammals has been well documented (Oliver 1981, Bell & Oliver 1992, Oliver et al. 1997, Narayan et al. in press). Fire is thought be a major driver to the rapid population decline of two cryptic mammals, the hispid hares and pygmy hogs, which had been well-adapted to tall and dense grasslands in the Terai region. In particular, it seems to be almost a tragedy for cover-dependent species that a sudden fire is enough to eliminate cover in tiny patches that are already fragmented, even inside PAs. For conserving the last remaining wild populations and the successful reintroduction of hispid hares and pygmy hogs, careful fire management is essential to reduce the risk of their extinction (Narayan et al. in press).

2.3. Changing fire policy and management

Natural fire called “bush fire” or “wild fire” has been perceived as an uncontrollable natural disaster causing devastation to life and property. In contrast, people have used fire to exploit natural resources more effectively; for instance, maintaining short grasslands and removing crop residuals to improve agricultural productivity (Buicini & Lambin 2002). In Australia, people regard fire as “a fact of life”, which implies their attitude to find better preparation to respond to natural fire rather than controlling it. However, most bushfire ignitions nowadays are caused by humans (Wills 2005). There are significant correlations between land-cover changes and fire presence at the tropical forest-savanna interfacing areas in the Amazon (Eva & Lambin 2000). Using fire as a forest clearance in already fragmented landscapes would result in more detrimental deforestation (Kodandapani & Sukumar 2004).

Fire management in the tropical world faces difficult decisions due to fundamentally conflicting demands between humans and nature. Safety concerns about severe wildfires have been a main force to control fire in fire-prone regions throughout history. Moreover, the risk of fire to life and property has not ceased in modern society, because residential areas have expanded towards more fire-prone lands in many tropical countries (Wills 2005). Management of fire is not confined to civilized society. Indigenous knowledge of fire management for preparing for a destructive wildfire and for utilizing natural resources has been inherited in ethnic communities in fire-prone regions.

Following an urgent need for conservation of tropical rain forests, many ethnic minorities were blamed as a major “problem” for deforestation because of their traditional fire regimes (Rakyutitham 2001). There have been gaps in theory and knowledge of fire impact on endemic ecosystems between official fire policies and indigenous fire practice, and it is more significant in PAs established in the colonial period by people from outside (Eriksen 2007). Originally, imposed fire suppression was for maintaining economically important components for modern forestry, agriculture practices or game reserves. Following domination by fire-suppression policies, many scientific researches have shown that the exclusion of fire has had adverse impacts on some ecosystems. As a result, fire policies have changed to increase conservation and promote biodiversity, particularly in Pas.

2.4. Fire management for conservation of tall grasslands

In general, grasslands throughout the world are easily modified to anthropogenic lands (Hoekstra et al. 2005). Little attention is paid in the tropics for grassland conservation compared with forests, and intact tropical grasslands have been rapidly disappearing; for example, only under 10% of natural grasslands in Cape York peninsula are preserved (Neldner et al. 1997). Most of the Terrai grasslands in India overlap with regions of high human population growth (Dyson et al. 2004). As a result, remaining natural grasslands are severely fragmented as tiny patches scattered around croplands or restricted inside PAs (Sawarkar 1999). From a wider perspective, most PAs in tropical countries have been maintained in better condition against land-cover clearance and agriculture encroachment than their surroundings, although many of them have failed in management both inside and outside PAs (Bruner el at 2001). In addition, it is not rare in India for several small villages to exist in PAs, and the main concerns for park managers tend to concentrate on human-related problems (Singh 1999).

Conservation of the Terai grassland ecosystem and its biodiversity has become an internationally and nationally urgent issue due to having responsibility for 12 mammal species, 29 species of bird and 5 species of reptiles which are globally threatened.

Understanding the mechanism of threats is necessary for effective conservation actions. Major threats to the grassland ecosystem are human interventions, frequent burning, harvesting of grass, heavy grazing and modification of river channels to prevent floods (Adhikary 1999, Chatterjee et al. 2006). Above all, widespread uncontrolled grassland burning is recognized as the most obvious threat causing dramatic change in the structure and distribution of vegetation, and it changes the probability of survival of endangered species dependent on the grasslands.

Considering the fact that the last remaining Terai grasslands are restricted inside PAs, fire management in PAs in India will play a key role for conservation of the unique but threatened ecosystem. Fire, integrated with seasonal floods, is a significant driver to promote ecological dynamics in Terai grassland because it is an important intervention to prevent succession to wooded lands. In the short term, species richness seems to increase in the post-burning period (Lehmkuhi. 1994, Peet et al. 1997). In contrast, there are fire-sensitive species which are extremely vulnerable to being exposed without cover (Bell & Oliver 1992, Narayan et al. in press).

In protected areas, fires are implemented nowadays mainly for conservation purposes. However, managers are forced to decide a way of controlling fire based on expertise without enough scientific evidence (Peet al at. 1997). Although there are some uncertainties in the dynamic and complex response of an ecosystem to a fire event, the use of accumulated fire records and research data enables fire managers to develop more strategic methods. The Kruger National Park in South Africa has recorded fire events over sixty years since 1948 (van Wilgen et al. 2004). Advanced research and management schemes in this large national park present useful information which might be applicable to other PAs where tropic savannas exist. Basically, scientists and managers assume that heterogeneity of fires could lead to heterogeneous structures and processes in the ecosystem. Patch mosaic burning (PMB) is one of the mainstream forms of strategic fire management which introduces fire variability into the landscape through the use of a dynamic mosaic across space and time (Brokett et al 2001).

If conservation managers aim to maintain biodiversity in any PAs, it should be taken into account that a single fire regime is not able to fill the demands of all species. In Australia, fine-scale mosaic burning was established, integrated with traditional practices of Aboriginal people (Russell-Smith 1997). Since there are still many difficulties for effective fire management, a better understanding of spatial and temporal patterns of fire based on accumulated fire records is fundamental to improve conservation management on the ground.

Following the assumption that a heterogeneity of fire patterns might generate a more diverse ecosystem, spatial and temporal patchy burning would be beneficial to maximize species richness (van Wilgen et al. 2004). Strategic fire management based on scientific evidence could be derived from long-term research and their data in different spatial and temporal patterns of fire, and this has already started in tropical savanna in Australia and South Africa (Biggs 2002, van Wilgen et al. 2004). To establish effective fire management, constant recording of fire occurrences, the mapping of fire distributions and analysis of the relationships between vegetation change and distribution of species will give managers baseline information to improve their fire regime. Focusing on fire-sensitive species as a goal of fire management should be also taken into account as the first priority for conservation.

2.5. Key components for establishment of effective fire management

In summary, according to this literature review, there are three key considerations for building effective fire management in habitat conservation for endangered species that are applicable to PAs containing tall grasslands in northern India.

1. Establishment of baseline data

For making better decisions of fire management based on scientific data, constant fire records are essential. Moreover, long-term monitoring of changes in fire occurrences, vegetation and population enables us to identify relations between fire management and its consequences in changing distributions of target species in conservation.

2. Maintaining heterogeneity of burning

Patchy mosaic burning has the potential to reduce the risk of severe population damage that will keep survival options open for a variety of species. In particular, setting out unburnt areas or maintaining a relatively long interval between burning could provide available cover to some fauna species.

3. Setting fire-sensitive species as the first priority of management

Not all species are resilient to fire in fire-prone regions. According to the evidence, some species are significantly susceptible to fire. For this reason, management should focus on maintaining the populations of some fire-sensitive species as a goal of conservation.

3. Study site

PAs in India cover over 1,500,000 km² or about 4.5% of the country. These consist of 85 national parks and 450 wildlife sanctuaries. Six national parks and 38 wildlife sanctuaries are found within the Terai grassland regions (Mathur 1999).

For this study, a PAs was selected on the northern hills of the Brahmaputra river basin in Assam District with importance to biodiversity conservation of the tall grassland ecosystem. The Manas National Park (MNP) plays a key role for maintaining an enormous number of species and their crucial habitats within a beneficial location connected with the Royal Manas National Park in Bhutan covering about 658 km² northward, as well as being the core area of Manas Tiger Reserve stretching from 89°45'E to 91 55'E long with a range of 2,837 km². The Manas National Park has a longer history and is relatively well-researched. Therefore, I used the park to estimate fire patterns on tall grassland habitat

The Manas National Park (MNP) stretches from 26°35'N to 91°15'E with an area of about 528.8 km², and has an elevation range of 50m to 250m above sea level with a gradual slope from the northern hills down to the southern boundary. The Manas River runs southwards through the park into the River Brahmaptra 50km south (Fig.2). These and other small rivers have deposited massive silt and rocks from Himalaya which make up the alluvial lands, suitable for the generation of grasslands. The Indian Monsoon rapidly advances in June and takes over the entire country by mid-September. It brings extremely heavy rainfall reaching up to 3,300 mm annually. The temperature varies between a mean maximum of 37°C in summer to a mean minimum of 5°C in winter. In a normal year, the winter dry-season starts in November and continues until reoccurrence of the pre-monsoon in March or April.

Fig. 2. The location of the Manas National Park.

The climatic conditions prevalent in the region especially characterized by the Indian Monsoon have a profound influence on the vegetation communities within the MNP. According to Lahker et al. (2007), four vegetation types are present in the park: semi-evergreen forest, mixed-moist deciduous forest, dry grassland and swampy grassland. Additionally, these alluvial grasslands occur in the lower reaches of the park, composed by *Imperata cylindrica, Narenga porphyrocoma, Phragmites karka* and *Saccharum sprotaneum*; grasses typical in Terai grasslands. Vegetation changes according to the differing edaphic conditions and elevation, which in turn provides diverse habitats for animal species. More than 450 bird species, 55 species of mammals, 50 reptiles and 3 amphibians have been recorded in MNP; it is recognized as one of the richest wildlife reserves in India. On the other hand, the park supposes 33 threatened wildlife.

Nine types of landscape elements have been identified in the park (Lahkar at el. 2007), including woodland, dry grassland, swampy grassland, flood plains, wetlands, cultivation, road networks, anti-poaching camps and fringe villages. Woodlands cover mostly northern areas continuous with the international border with Bhutan and the south-west area close to the Manas River. Grasslands occupy almost one third of the parkland, and its large part is facing villages encroaching the southern part of the park. Additionally, two large areas are distinguished by human encroachment at the edge of the southwest and extreme southeast of the reserve (Fig.4).

After designation as a World Heritage site in 1985, the MNP experienced tribal and civil unrest accompanying illegal logging and poaching of wild animals (Vigne & Martin 1998), until the signing of an agreement between indigenous groups and the government of India in 2003. Nowadays, the major threats to biodiversity are human encroachment, illegal extraction of natural resources and uncontrolled burning. In particular, frequent grassland burning has had substantial impacts on the last remaining wild population of pygmy hogs and other fire-vulnerable species (Mathur 2007).

4. Fire Data

Burning only occurs during the dry-season in the MNP. This study employed active fire data derived from MODIS (or Moderate Resolution Imaging Spectroradiometer satellite images. MODIS is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS orbit the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths (MODIS Technical Specifications). Fire on the Earth's surface can be detected by MODIS as a thermal anomaly using data from the middle infrared and thermal infrared bands.

Active fire locations are processed by the MODIS Rapid Response System using the standard MODIS MOD14 Fire and Thermal Anomalies Product. Each active fire location represents the centre of a 1 km pixel that is flagged by the algorithm as containing a fire within the pixel. The spatial resolution is 100 m^2 at 50% probability in usual conditions, or 50 m^2 of fire flaming detectable at nearly 100% probability under ideal conditions, such as being free of clouds, heavy smoke and sun glint. No data on burned areas is currently available. Although MODIS can only supply information on the location of fires, access to satellite remote sensing data allows managers to understand the overall spread of fires in inaccessible areas and allows observation without direct disturbances on a target site (Longley et al. 2005).

MODIS active fire data from November 2000 to May 2008 were available for analyses for the present study (Giglio 2007). The dataset comprised daily fire observations acquired from the Terra satellite; Terra overpasses the study area a total of four times daily. Active fire data used herein amounted to a total of eight dry-seasons for the nine study years. Each fire point contained information on the exact time and day of detection, a global georeference system location (longitude, latitude), the brightness of the fire and classified confidence level. These data were supplied by the Fire Information for Resource Management System (FIRMS) of the University of Maryland.

All land-cover datasets of the MNP were provided by the local NGO, Aaranyak. Remote sensing satellite data analyses and ground surveys were conducted by Aaranyak, where seven land-cover types (woodland, grassland, wetland, swampy land, river channels, river sand and agricultural land) were identified and mapped. Additionally, the locations of villages and campsites were combined as GIS map layers. More detailed information can be found in Lahkar et al. (2007).

The MODIS active fire dataset was clipped with the MNP boundary shape file using the same regional coordinate system (Fig.3). The seven land-cover types described above were represented as four main land-cover types (woodland, grassland, wetland, rivers); wetland and swampy land were combined into 'wetland' and river channels and river sand into 'rivers' due to lack of sufficient data. Agricultural land was excluded, since no fire was recorded here.

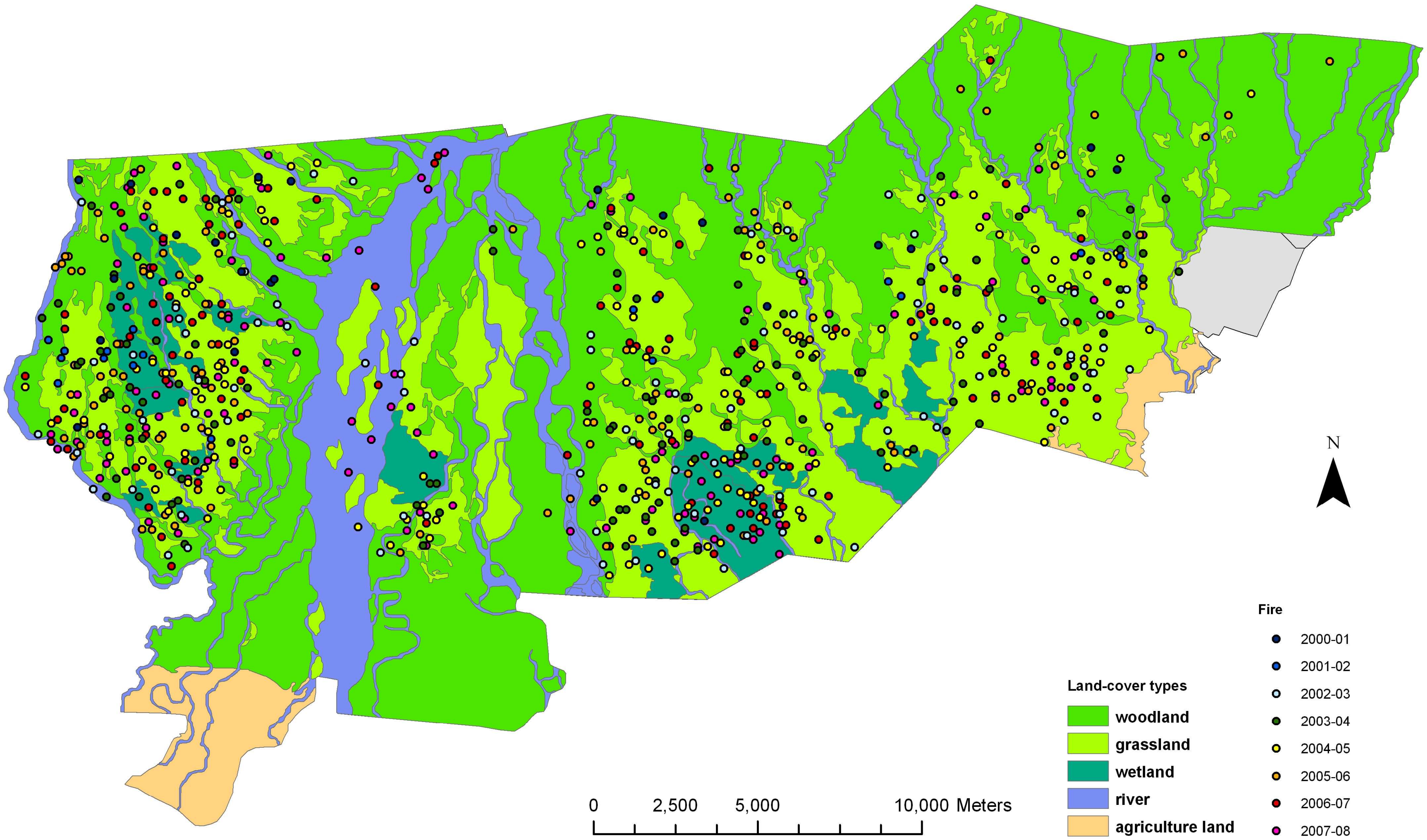


Fig. 3. Fire occurrences in the MNP during 2000-2008. The map was combined land-cover shape files and all fire point files in each dry-seasons from 2000 to 2008.. The projected coordinate system of this map is Everest_Bangladesh_Polyconic

5. Methods

A total of 781 fire incidents were recorded in the Manas National Park (MNP) during the study period (2000–2008). No fire was detected during wet seasons.

5-1. Temporal patterns in fire frequency were investigated.

5-2. The relationship with land-cover was investigated.

5-3. Spatial patterns in fire distribution were estimated in relation to

- 5-3-1. distance from boundary, roads and rivers.
- 5-3-2. intensity in areas identified as more likely to be burned.

5.1. Temporal patterns

Temporal changes in fire frequency for the whole area of the MNP were investigated on a monthly and yearly basis for dry seasons (October-May) from 2000 to 2008. Monthly changes were studied for each season as well as for the eight seasons combined.

5.2. The relationship with land-cover

The total incidence of fire during the study period was counted for the four types of land-cover (Woodland, Grassland, Wetland and River) described above, and fire density calculated as the number of fires per km^2 of the land cover area. Fire occurrence and density in each land cover type were also obtained for three distinct periods of the dry season:
1) early (October–December); 2) mid (January–February), and 3) late (March–May).

The effects of land cover and the period of the dry season on fire occurrence were investigated using a contingency table analyzed by chi-squared test. Since land-cover types varied in size and could have a large effect on the response variables, fire frequency values were divided by areas, and multiplied by 100 to obtain an integer for inclusion in the chi-square test. The explanatory variables were two factors: land cover with 4 levels (woodland, grassland, wetland and rivers) and dry season period with 3 levels (early, mid and late).

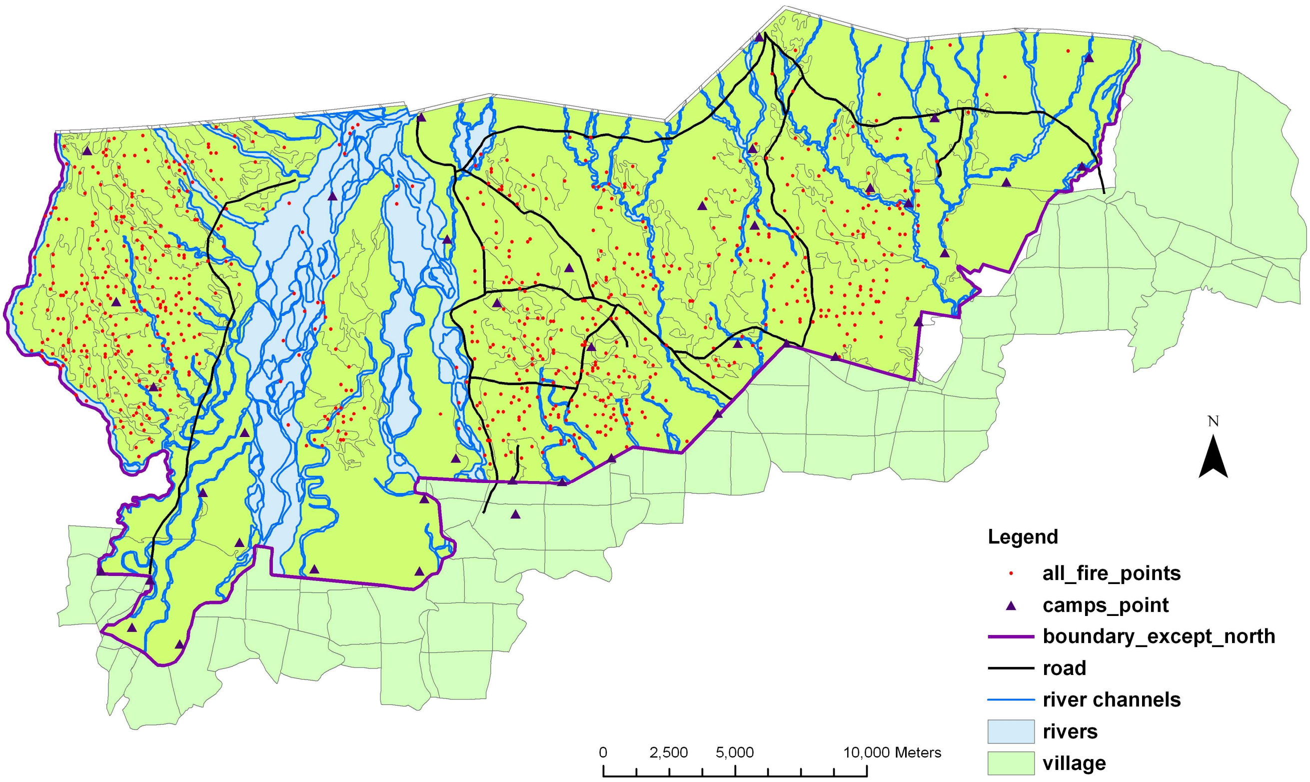


Fig. 4 The land-use in and around the MNP. All fire from 2000 to 2008 was combined together.

5.3. Spatial patterns

5-3-1. The effect of distance from park boundary, roads and rivers

Park boundaries, roads and rivers, as surrogates of accessibility to the park (and therefore probability of ignitions), were used to correlate with fire distribution. The boundary corresponding to the international border with Bhutan was not included as a boundary layer for the reason that there is no access, so the park border line from the extreme north-west to north-east including all the southern border of the park was defined as the boundary line. The river and road were used as one network (Fig. 4). Using these three line vector layers, the minimum distance from a fire point to the nearest point on the line to the park boundary, roads and rivers was calculated using the GIS software, ArcMap.

To investigate the relationship between fire occurrence and distance from each geographical feature, distance values (0–11200m) were first partitioned into 100m-intervals and fire frequency counted for each interval to obtain a set of response and explanatory variables, fire frequency and distance, respectively. The dataset was then analyzed by regression, using a Generalized Linear Model (GLM) with a log link and Poisson errors. The statistical software R was used for the analysis.

5-3-2. Fire intensive areas

To identify areas within the MNP that have a high concentration of fire occurrence and evaluate fire distribution patterns at a landscape level, all active fire data were combined together into one layer and converted into a raster dataset for density analysis using a kernel density estimation tool in the GIS software ArcMap. Spatial distribution of the fire points collected during all eight years were modeled as density "kernel" functions which weights frequency of location based on 2-dimensional Gaussian distribution, with the density represented as contour plots on a surface.

6. Results

6.1. Temporal patterns

The total yearly number of fires recorded within the MNP increased substantially from around 20 at the start of the study period (2000-1, 2001-02) to over 100 after 2002-03, peaking at 157 in the 2005-06 dry season (Fig. 5).

Fig. 5 Changes in the total number of fires from 2000 to 2008 in the MNP. The years (2000_01, 2001_02, etc.) represent the dry seasons between October 2000 and March 2001, between October 2001 and March 2002, and so on.

There was a large inter-annual variation in monthly patterns of fire occurrence; the most significant being 2003-04 which had the highest number of fires in February (Fig. 6) 2005-06 was an exceptional year where 43.9% of fires occurred in the early dry-season and fewer in mid season, increasing again in March.

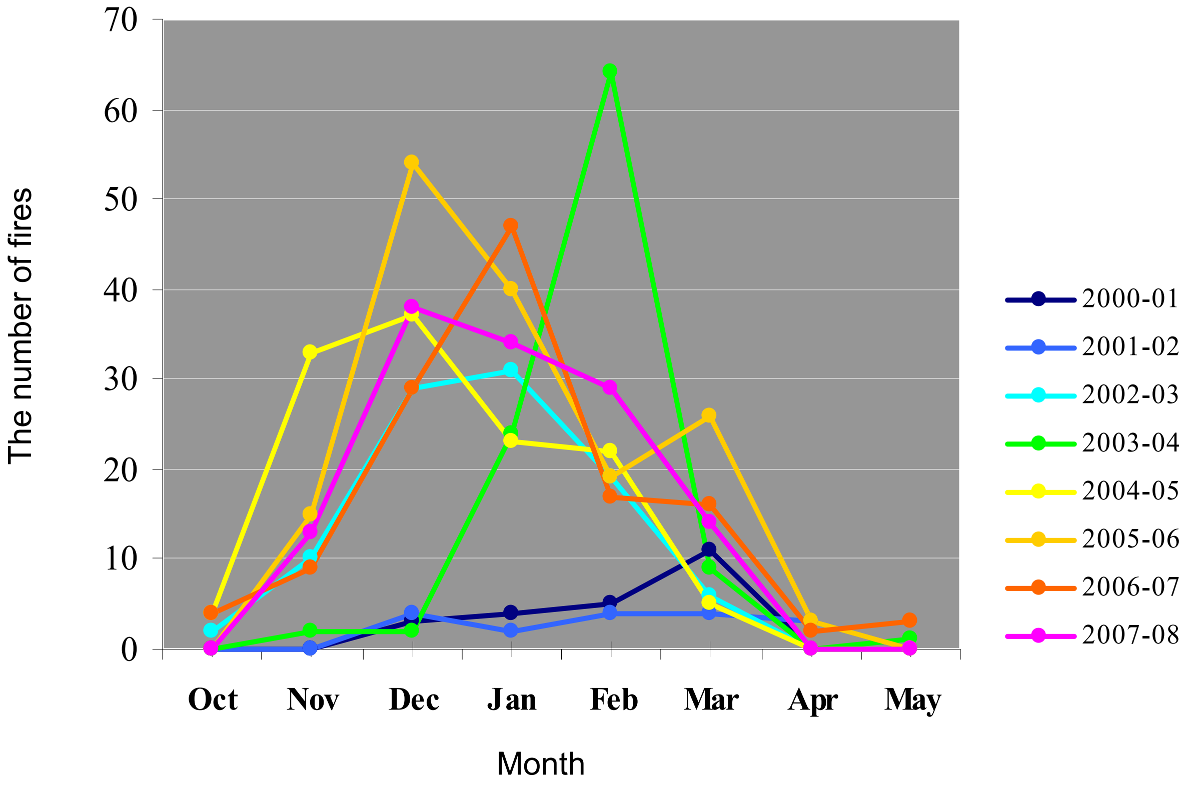
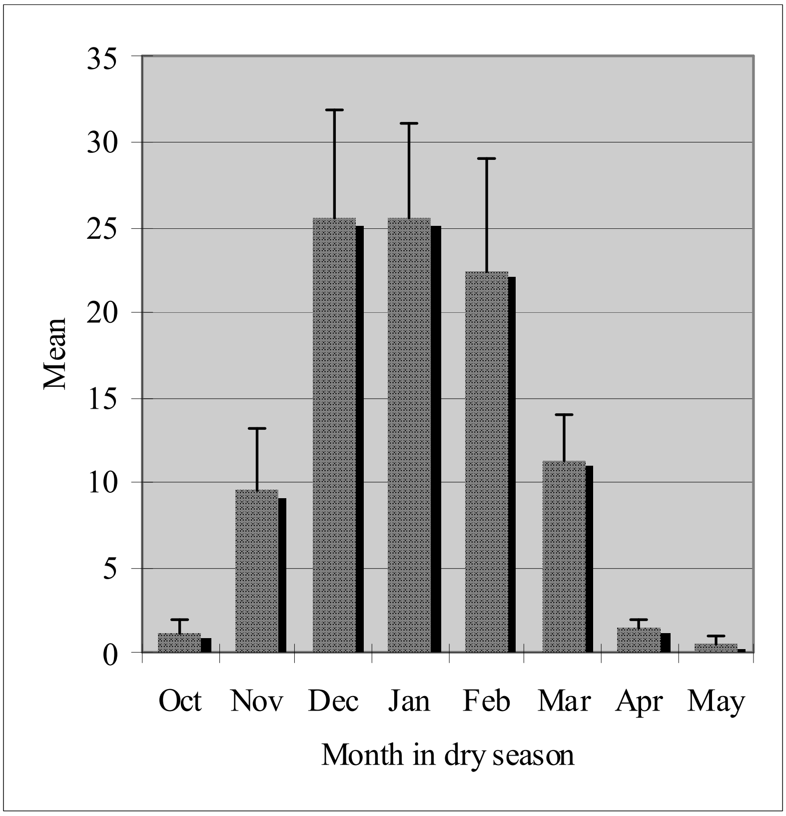


Fig. 6. Yearly and monthly changes of total number of fires from 2000-01 to 2007-08 in dry-season in the MNP. The years (2000_01, 2001_02, etc.) represent the dry seasons between October 2000 and March 2001, between October 2001 and March 2002, and so on.

For all years combined, a total of 85 % of fires occurred between December and March. The transitional period before and after the monsoon season (the first and the last two months of the-dry season) experienced fewer fires. The common pattern of fire occurrence was a distinct increase from December to January after a low during October-November, with the number of fires declining after February and dropping even further from March to May (Fig. 7). According to the mean of fire counts among the eight dry seasons shown in Fig.7, December and January had the highest frequencies of fire (25.5 ± 6.336 and 25.5 ± 5.673 respectively), followed by February (22.38 ± 6.638).

Fig. 7 The mean of monthly fire records from 2000-01 to 2007-08 in dry season. Error bars represent 1 standard error of the mean.



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Mean	1.25	9.5	25.5	25.5	22.38	11.38	1.5	0.625
Standard Error (1 se., n=8)	0.648	3.674	6.336	5.673	6.638	2.577	0.500	0.375

6.2. The relation with land-cover type

Almost half of the total land area in the MNP is woodland, 31.8% grassland, 13.2 % and 6.4% river and wetland respectively. During the study period, over 416 fires were detected in grassland; over half of total fire records (53.3%). The highest density of fires occurred in wetland areas, compared to in grassland, with the lowest incidence in woodland.

Table. 1. Summary of fire distribution in land-cover types in the MNP. Total fires is total number of fire occurred from 2000 to 2008.

	Total fires	% Fires	Area size (km^2)	% Area	Fire density / km^2
Woodland	189	24.2	256.9	48.6	0.736
Grassland	416	53.3	168.2	31.8	2.473
Wetland	122	15.6	33.7	6.4	3.620
River	54	6.9	70.0	13.2	0.771
Total	781	100.0	528.8	100.0	

Temporal changes in the number of fires reported per month differed by land-cover type (Table. 2). The means of fires reported varied as 15.25 ± 12.73 fires per month in wetland, but was more regular in grassland and woodland. Fires in woodland were more evenly distributed than in grassland and wetland.

Table.2. Monthly changes of fire occurrence in land-cover type from 2000 to 2008 in the MNP. The data presented that the number of fire recorded in different land-cover types. s.e., is standard error. (n=) is the total number of fires

	Mean ± SE	Highest (month)	Lowest (month)
Woodland	23.5 ± 17.28 (1 s.e., n=189)	58 (Feb)	1 (Oct, May)
Grassland	52.12 ± 40.01 (1 s.e., n=416)	127 (Jan)	1 (May)
Wetland	15.25 ± 12.73 (1 s.e., n=122)	46 (Dec)	0 (Apr, May)
River	6.75 ± 4.04 (1 s.e., n=70)	16 (Dec)	0 (Oct)

.

The temporal distribution of fires expressed as proportions of fire frequencies during the the early, mid- and late periods varied greatly among the land cover types (Fig.8). For example, fire frequency in wetland and river was highest in early dry-season, while fire in woodland was concentrated in mid dry-season. Grassland had a different pattern from woodland showing high frequency in mid season with higher percentages in early season than woodland.

Seasonal data for all years combined, showed that most grassland burning occurred during mid dry-season (January and February) (Fig.9). Furthermore, almost a half of all burning were in early and mid season in grassland (46.9%).

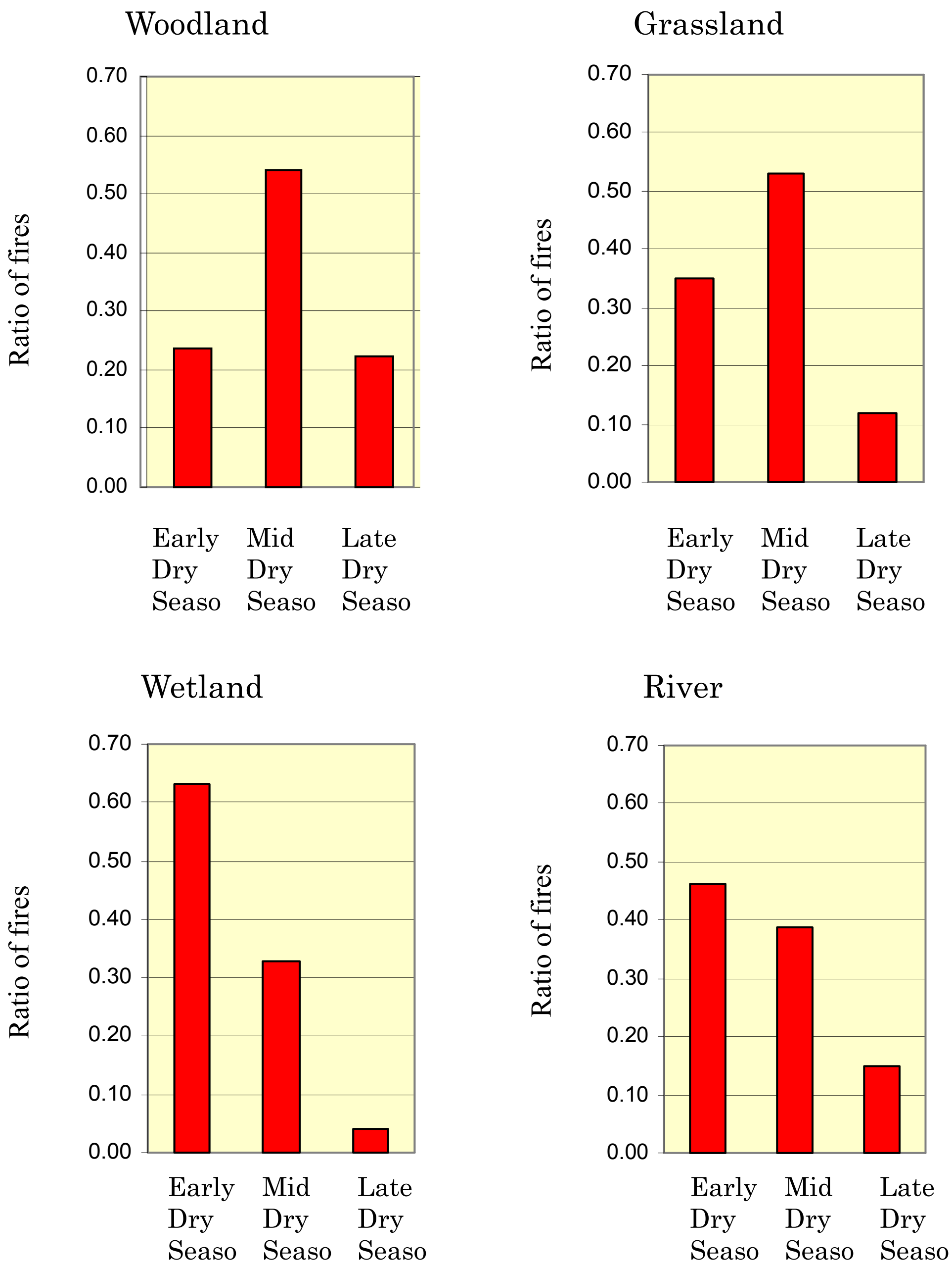


Fig. 8 Proportional changes of land-cover in different season.

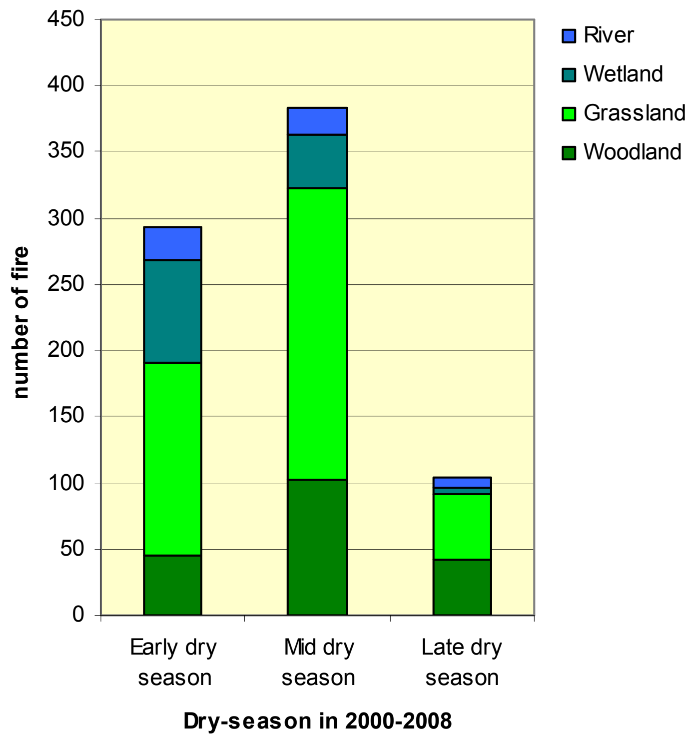


Fig. 9. The proportional changes of the number of fire in land-cover types in the three dry-season

The chi-square test was used to analyze the possibility of whether the contingencies actually happened in the observed data, in particular, to assess higher frequency of grassland burning in mid and late dry-season. Then, statistical significance of the relationship among the 12 categorical variables was tested (Table. 3). The result of chi-square test evidenced that the chi-value (77.03) was far greater than critical value (16.811, 6d.f), so, the null hypothesis assumed the values independent was rejected. Therefore, the significant differences between observed and expected data were confirmed ($p < 0.0001$). This means the grassland burning in the mid and late dry-season were significantly greater than expected (mid dry-season O = 131, E = 103.18, late dry-season O = 29, E = 23.11).

Table.3

Fire density (per 100km²) and land-cover types at the MNP.
O-value means observed fire data and E-value is expected value calculated from total number of each season and land-cover types. The result of Chi-square test was χ^2=77.03 with P<0.0001, and its critical value was 16.811 at df=6, p=0.99.

	Woodland		**Grassland**		**Wetland**		**River**		**Total**	
	O-value	E-value	O-value	E-value	O-value	E-value	O-value	E-value	O-value	E-value
Early dry-season	18	35.98	87	120.08	228	175.51	36	37.43	369	369.00
Mid dry-season	40	31.10	131	103.81	118	151.72	30	32.36	319	319.00
Late dry-season	16	6.92	29	23.11	15	33.77	11	7.20	71	71.00
Total	74	74.00	247	247.00	361	361.00	77	77.00	759	759.00

6.3. Spatial patterns

6-3-1. The effect of distance from park boundaries, roads and rivers

Mean distances from all recorded fire points to the park boundary, roads and rivers are summarized in Table 4. The largest mean distance was 3,693.31 ± 86.31 m to the boundary. The mean distance of fires to roads was less than to the park boundary 1,974.66 ± 58.69 m, Distances to rivers were on average lower than for roads and the boundary (868.32 ± 39.52).

Table. 4. Summary of distances of fire occurrences during 2000 to 2008 from the park boundary, roads and rivers in the MNP. The data represented at unit of meters, each fire point was measured the distance from closest point of line geographical features. Boundary means the park boundary except the northern boundary line.

	Mean ± SE (1 s.e., n=781)	Minimum	Maximum
boundary	3,693.31 ± 86.31	1.38	11,330.13
roads	1,974.66 ± 58.69	4.51	7,355.21
rivers	868.32 ± 39.52	0.34	11,172.79

There were statistically significant ($p<0.001$) correlations between fires and distances to all geological features. The closest fit between the observed and predicted fire frequencies was found for the river-distance dataset. (Fig.10. c)..

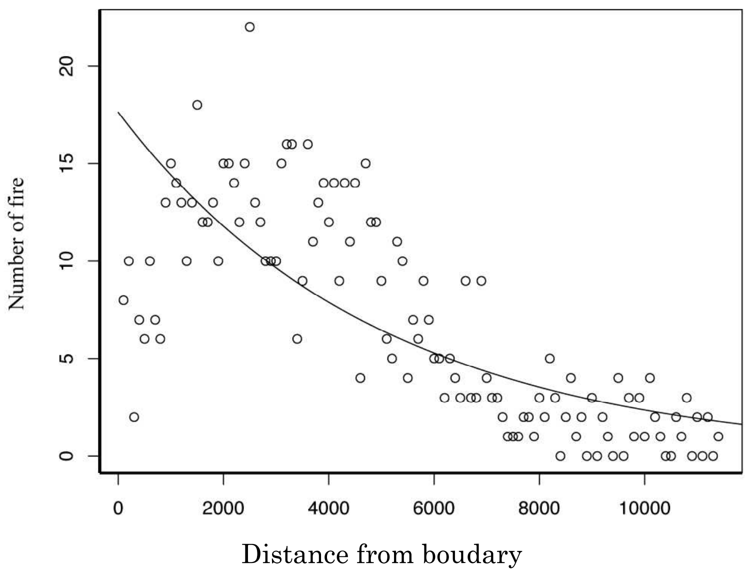


Fig. 10, a. The correlations between distances from boundary.. The observed (2) and predicted (—) fire frequencies in relation to distance from the park boundary. Slope = -2.006 e-04, SE = 1.228 e-05, z value = 16.34, P = 2 e-16.

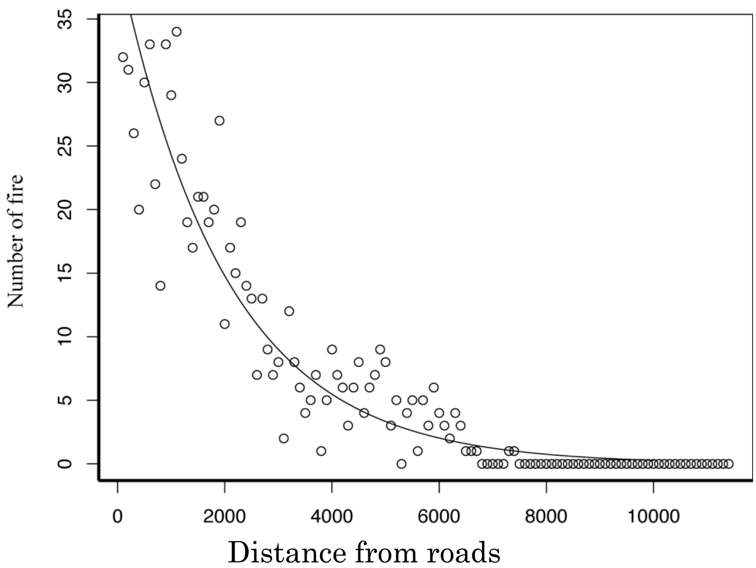
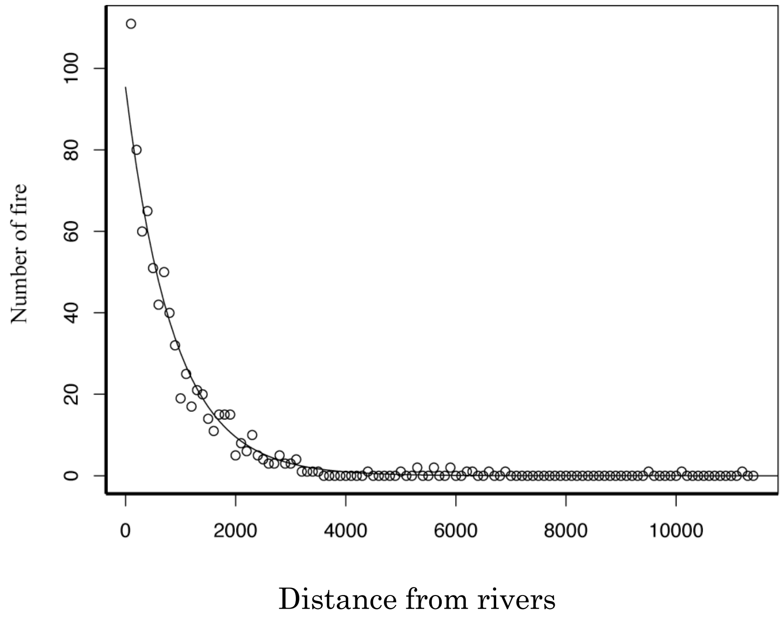


Fig. 10, b. The correlations between distances from roads. The observed (2) and predicted (—) fire frequencies in relation to distance from the roads. Slope = -4.996 e-04, SE = 1.886 e-05, z value = -26.33, P = 2 e-16.



Fog. 10. c The correlations between distances rivers. The observed (2) and predicted (—) fire frequencies in relation to distance from the rivers. Slope = -1.152 e-03, SE = 4.126 e-05, z value = -27.93, P = 2 e-16.

5-3-2. Fire intensive areas

The fire density map (Fig. 11) indicated that fire locations were not evenly or randomly distributed throughout the MNP. In fact, fire distribution was not uniform, and intensively burnt and unburnt areas are explicitly revealed.

In particular, three distinct areas of heavy burning were identified; the largest concentration was located along the furthest western part of the park (longitude 90°50 E). Another heavily burnt area was located in the southern part of the central area of the MNP, where the major concentrations occurred on grassland and wetland. This densely burnt area stretches northwards along the grassland patches in that part of the park. The third fire aggregation significantly overlapped with grasslands along the south-eastern park area, close to the encroached region.

There were also some detectably unburned areas, such as the 2 or 3km fringe along the Manas River which had no fires recorded by MODIS during the last nine years. Furthermore, the large areas covered by woodland in northern part of the MNP had a few fires except along the small rivers.

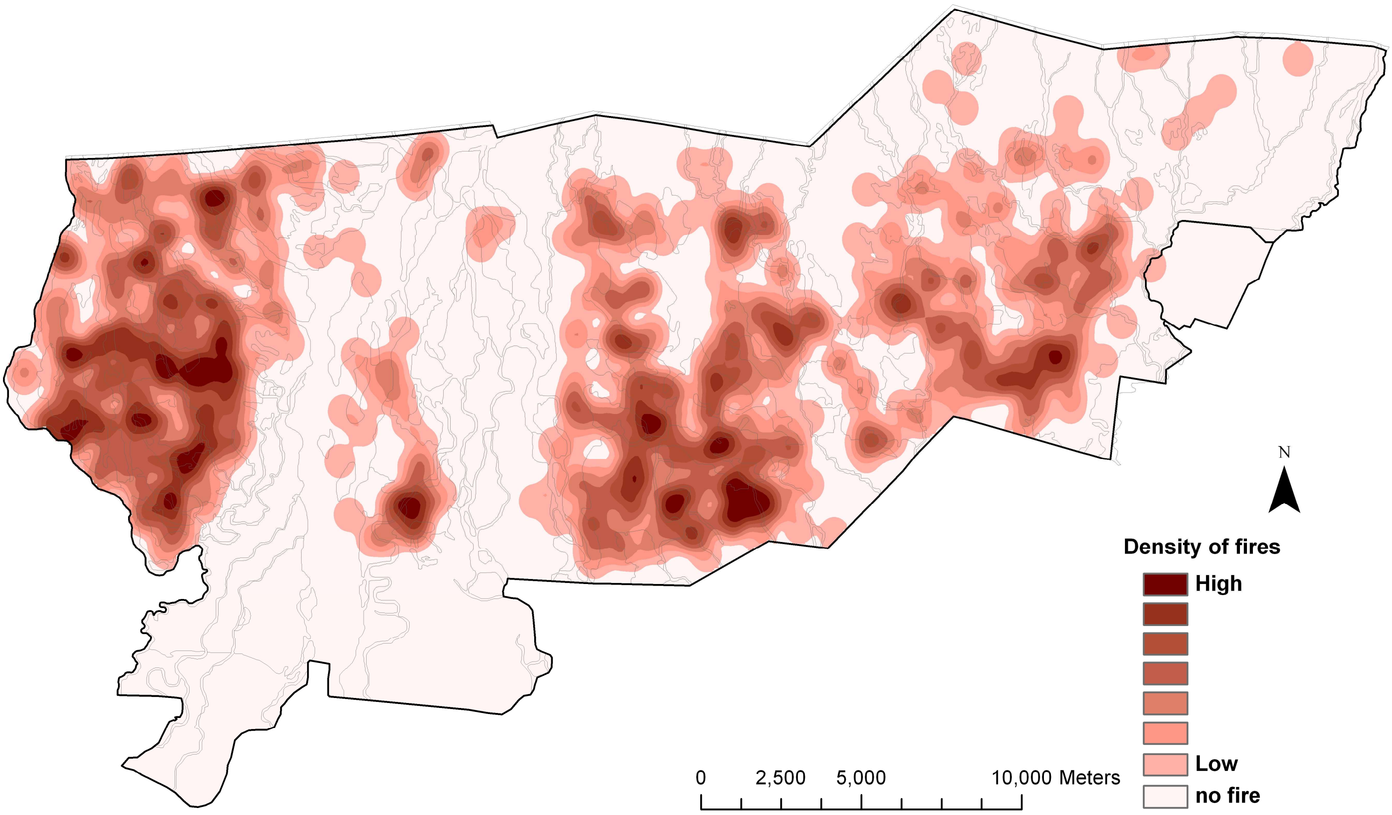


Fig. 11 Density of fire occurrences in the Manas National Park. The result of Kernal density estimation presents the graduation of colors showing degree of intensity of fires.

7. Discussion

7.1. The use of remote sensing fire data

Fires influence global change and tropical ecosystems through their impact on land-cover dynamics, atmospheric composition, and the global carbon cycle. As such, many institutions are interested in the use of satellites to monitor and quantify fire occurrence in a variety of landscapes. However, the major issue in the use of remotely detected fire data is limitations of the derived products and the incidence of omission errors (Eva & Lambin 1998). Oversight of fires was likely if the duration of a fire was shorter than six hours, since fire observations are made four times a day from the Terra AM (10:30 and 22:30). In a survey to test fire detectability by MODIS, Jin et al. (2003) recorded twice as many fires on the ground as were registered by MODIS. Whether this is the case for the data gathered for the Manas National Park (MNP) is not known. However, significant fires, both in distribution and frequency, are investigated using MODIS. Furthermore, one of the strengths of MODIS is the synoptic source of information derived from regular observation in a precise time frame from satellite (Reeves et al. 2006). MODIS fire products have built and improved on the experience of fire assessment primarily using the NOAA-AVHRR and GOES systems. Currently no other system provides the instrument characteristics needed for an effective global fire monitoring programme. The MODIS sensor was designed to include characteristics specifically for fire detection and provides a unique capability over existing sensors in terms of fire monitoring.

The major limitation in this study was the lack of information on the size of fire-affected areas essential to estimate fire impact on vegetation or landscape changes. Many users are ultimately interested in the area of land that is burned, and some supplemental research has been undertaken through the detection of burn scars using higher resolution radiometers, such as AVHRR and ASTER (Eva & Lambin 1998). Currently, MODIS offers unique spatial and radiometric capabilities for burn scar detection. An automatic procedure for burn scar detection has been developed and now implemented in the

MODIS production stream (Roy et al, 2005). The products will be available at full resolution and as spatial summaries and temporal composites. In this study, MODIS active fire data (at 1km^2 pixel resolution) can be used to calculate the maximum size of the burned areas, but this is coarse. Given the refinement and improvement in the detectability of burned areas being developed by MODIS, this should be possible in the near future (Giglio 2007). Despite this limitation, MODIS active fire data has been most useful in identifying temporal patterns of burning in the MNP, for detecting seasonal and yearly variation in the number of fires.

Landscapes in the MNP were classified into seven broad types, since more refined analyses of variation within habitats (e.g. different grasslands classified by height or composition) was not possible. However, results from this study clearly showed that most fires occurred in grassland areas. Moreover, distance analyses reveal that most fires occurred closest to roads, rivers and the park boundary.

Yearly changes in the number of fires in the MNP indicated that a significantly higher number of fires were recorded during 2002-2003. Before this period (since 1989), the park was inaccessible to local people due to political insurgency by the Bodo (a major local tribe in the Manas region), which had stopped local people entering the protected areas (PAs) (Vigne & Martin. 1998). On the other hand, because the fire records used in this study could not discriminate between controlled and uncontrolled burning, it is also possible to assume that the increase in fires reflects the use of prescribed fires started by park staff. The detection of illegal burning within the park would be possible if records of prearranged fires (including time and exact location) were kept by park staff, to contrast with data supplied by MODIS. Although active fire data from MODIS has been claimed as a “snap-shot” measurement, it is a practical tool that can be used to identify areas at risk of fires by giving park managers information about where uncontrolled burning takes place.

7.2. Seasonality in grassland burning

The extreme alternation of wet and dry-seasons in tropical or sub-tropical regions produces savanna vegetation. An annual period of productivity during the wet season inevitably produces growth which dries out and becomes flammable during the dry-season. Burning of these grasslands by aboriginal peoples or through the natural incidence of lightning has dominated these landscapes for millions of years in Australia. (Russell-Smith et al. 2000). Many studies have shown that late dry-season burning has more significant impacts on vegetation cover than burning in the early season (Bucini & Lambin 2002). For example, in a study in the Kruger National Park, South Africa, the severity of fires was shown to be greatest at the end of the dry-season due to the accumulation of higher fuel loads (Govender et al. 2006). Additionally, the significant factor is always fuel moisture content, which is generally lower during the dry-season and therefore material is more flammable (van Wilgen et al. 2004).

Natural fires, generally infrequent but often intense, kill many plants, thereby creating opportunities for new species to colonize from seed already present or blown or carried onto site. Typically, changes in vegetation generated by fire in tropical savannas are not dramatic and recovery is rapid, although the nature of the impact and recovery varies with the co-related time of year and intensity of the fire. Thus for the rest of the year, the structure and resource availability of the habitat created by the fire and the short-term recovery of the vegetation remains until the next wet season, and this suits different species to differing degrees.

Wildlife managers, such as those in the MNP, use prescribed burning for two main reasons: to manage the build-up of flammable fuel (live and dead vegetation), consequently reducing the impact and difficulty of suppression of wildfires, and to increase grazing lands for large herbivores in aid of the park's biodiversity and other environmental values. Burning of grasslands during the early dry-season has been recognized as the optimal method to prevent more serious consequences by wildfire. However, the evidence to support this is equivocal, since at least in an experimental study in tropical savannas in Northern Australia, the impact of early and late burning on riparian vegetation and small mammal populations was not statistically different (Andersen et al. 2005).

7.3. Distribution of fires in relation to moisture

In this study, the highest densities of fires were found in wetland areas. This can be explained by the fact that wetlands dry up during the winter months in this region (Sah 1999, Mathue et al 2007), perhaps as a consequence of higher fuel loads accumulating in these landscape type. This effect is further confirmed by the correlation between the number of fires and the distance from river channels. In a study of fire impact in Australia, riparian vegetation was highly sensitive to fires (Andersen et al. 2005). Thus, the risks to biodiversity in the wetland and river areas in the MNP are likely to be greater despite the proximity to water bodies.

7.4. Impact of frequent fire and its mitigation

This study clearly indicated that there were three main areas within the MNP which had a significant concentration of fires; these areas were being burnt every year. Data on the effect of burning in these areas, especially their burnt area sizes, is currently unknown but information gathered from other areas indicates that frequent burning will inevitably cause major ecological impacts on grassland and wetland vegetation. For example, savanna tree mortality was higher in more intensively burnt areas (van Wilgen et al. 2004), because longer post-fire periods allow trees to grow tall enough to survive during sequential burning. Furthermore, early successional species were more prevalent in frequently burned areas while more midstorey plants and log cover were found in low frequency areas (Fenner & Bull 2007).

In early successional stages, grasslands in the Terai are assemblages composed of short grass species, *Imperata cylindrica*, in relatively drier lands, often being preferred by grazing (Sah 1999). If there are no disturbances such as fire, floods or grazing, the short grass community will become taller grassland dominated by *Saccharum spontanuem*. Eventually, *Saccharum* grassland will convert into thatch-scrub savanna, suitable for cover-dependent species (Oliver 1981, Yadava 1990, Peet et al.1999). Such differences in plant composition and structure are apparent when areas of high and low fire frequency are compared. For example, Fenner & Bull (2007) found that plant diversity and habitat structures were higher in the less burnt zones. The study concluded that fire frequency greatly affected the extent of succession. Because of these results, conservation managers have argued that burning of patches at different sites is the most satisfactory scheme to ensure maximum biodiversity in grassland areas. Thus, patchy mosaic burning (PMB) is currently popular among conservation managers because it is based on the assumption of the positive relations between fire heterogeneity and biodiversity. However, some studies have shown that a number of species showed no differences in their population numbers between PMB areas and conventional fire treatment areas (Parr & Andersen 2006). More importantly, defining the ideal mosaic size of patchy burning is difficult. PMB should be implemented within a strategic management scheme that can predict the influences of fires caused by a completely controlled regime, and therefore there is a need for a rigorous on-going monitoring system. Hence, PMB could contribute to maintaining biodiversity positively only if it is integrated with spatial and temporal prediction models (Russell-Smith et al. 2003). Setting less frequently burned areas, unburned zones or long fire return intervals may be more practical in the case of the MNP rather than continuing with the current system.

7.5. Recommendations for fire management in the Manas National Park

The significant negative correlations between fires and distances from roads and the boundary suggest that grassland burning was human-induced, and the identified intensive areas indicate that there are still on-going threats to the MNP grasslands. In order to reduce the threats and to conserve grassland diversity and its inhabitants, the establishment or improvement of effective fire management is essential. There are three important recommendations from this study that can help minimize the risk of detrimental damage on both grassland diversity and species dependent on the grassland habitat.

First of all, prioritizing fire-sensitive species as the target in fire management is a practical way to lead conservation outcomes effectively. Clear targets help managers to set clear goals and make a clear evaluation of each fire regime with guidelines containing the species requirement. The typical cover-dependent species, e.g. pygmy hogs, hispid hares and Bengal Florican, are endangered species that overlap in their distribution in the MNP, and therefore must be seen as highest-priority as fire-sensitive species. To meet their demands for habitat, identifying key successional stages of grasslands to each is essential. This requires maintaining more diverse grassland assemblages, and this would also benefit other species and biodiversity as a whole.

Secondly, there is a need to prevent further extension of highly intense fires, so unburned areas and a longer interval period between burning should be established. For managing the frequency of burning, patchy mosaic burning has been widely recommended. Besides, PMB is not suitable for this site because of limited supporting evidence and difficulties of integrating spatial and temporal patterns of fire.

As some park managers in India suggested (Mathur 1999), the largest natural disturbance caused by heavy rainfall is inevitably an important factor for grasslands successions in Terai regions. The significant correlations between fire and the distance from rivers analyzed in this study reveal that grasslands are largely disturbed by water in the wet season and fire in the dry-season. Therefore, a precautionary approach has the potential to prevent unpredictable consequences of excessive controlled or uncontrolled burning that might be occurring in the MNP. As a result, patchy mosaic burning needs to be replaced by unburned areas or longer post-fire areas that can ensure refuges for the fire-sensitive species.

Finally, it is clear that much more research should be undertaken, in particular, focusing on the three fire frequent areas to investigate the extent of burning and to estimate their impact on grassland and riparian vegetation with aquatic diversity. Studying the relationship between flooding and burning together is necessary to estimate influences on vegetation changes, and will provide baseline information for more effective fire management.

In conclusion, the threat of frequent burning on grassland still remains in the Manas National Park. To conserve the unique grassland diversity together with unique fire-sensitive endangered species, recommendations for the Manas fire management are to target fire-sensitive species, spatially and temporally unburnt refuges, establish a fire record system and further study two integrated disturbances, fire and water.

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