Estimating Potential Fire Danger within the Siberian Tiger Habitat

by

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Abstract

Forests of the Russian Far East, designated by UNESCO as a World Heritage site and home to the Siberian tiger - a highly endangered species with approximately 350 adult tigers remaining in the wild, are severely threatened by wildland fires. The frequency of catastrophic fire events is predicted to rise due to global warming trends. The large size and mountainous terrain of the study area and government control of data sources make remote sensing the only viable source of data for spatially explicit analysis. The analysis of spatio-temporal occurrence of fire events from MODIS (Moderate Resolution Imaging Spectroradiometer) and meteorological records for the 2001 – 2003 period showed that catastrophic fires in the study area are driven by the disruption of the monsoon climate. A map of Fire Danger incorporating Risk of Ignition and Potential Fire Behavior was created to evaluate areas of high risk within the Siberian Tiger habitat during catastrophic fire events. The results show that fire ignition strongly correlates with human disturbance. Both area accessibility through major roads, railroads and rivers and land use have a direct impact on the frequency of fire ignition. In addition, fire frequency in evergreen needle-leaf forests which constitute 25% of Siberian tiger habitat increases as a function of the intensity of a given fire season. Over 60% of the potential Siberian Tiger Habitat falls within “moderate” – “high”- “very high” fire danger zones, which indicates species vulnerability during catastrophic fires. Future research will aim at developing a regional remotely sensed data driven model for analyzing Catastrophic Fire Threat to the Siberian Tiger, which will incorporate Habitat Preference analysis and Habitat Recovery Potential in addition to Fire Danger for several climate change scenarios.

1. Introduction

The Russian Far East is a unique area of high biological importance part of which was designated by the United Nations Educational Scientific and Cultural Organization (UNESCO) as a World Heritage Site (UNESCO, 2002). The integrity of the forests covering 70 percent of this area (Miguelle et al., 1999b) is threatened by human disturbance and wildland fires. In Russian boreal forests fire is the primary factor controlling ecological succession and carbon storage (Fraser and Li, 2002). Wildland fires impact and reshape forests (Lasko, 2002) causing reduction and fragmentation of the native vegetation and impeding forest regeneration (Bushnell, 2002). The past fire history shows that catastrophic fire events are recurring incidents in this area: wildland fires burned 800,000ha in 1976 and over 2.5 million ha in 1998 (WWF, 2001; Bushnell, 2002).

In addition to the overall importance of the Russian Far East in terms of biodiversity, this area is home to one of the most critically endangered species in the world – the Siberian Tiger (Charbonneau, 1998). In 1998 and 2001 the impact of large wildland fires on the Siberian Tiger gained international media attention (Charbonneau, 1998; Chernyakova, 1998; 5tigers, 2001; Brown, 2001; WWF, 2001). According to the World Wildlife Fund (WWF) large amounts of funding (over 1.5 billion dollars for 1998) and resources have been put into fighting wildland fires in areas considered important for the Siberian Tiger (WWF, 2001).

In the light of the considerable warming trend of the changing global climate (Hansen, 1999) with its particularly strong effect on the boreal regions (US Global Change Research Program, 2003), occurrence of wildland fires in the region is predicted to increase (Stocks, 1993). Consequently, it is important to study the effects of wildland fires on the Siberian Tiger habitat for successful management efforts in tiger conservation.

Wildland fires occur over an extremely broad range of areas and conditions and often over remote areas with limited access. Remote sensing is considered a valuable source of timely and consistent data about wildland fire impact (Rogan and Yool, 2001). The study area of this project is over 30 million hectares, and is dominated by the Sikhote-Alin Mountain Range. In addition to the very large geographic area and limited access, there is considerable constraint on local data availability due to government control of data sources. Remotely sensed data and derived products became major sources of fire observations as well as other categories of data for the Russian Far East used in this research.

2. Study Area

Panthera tigris altaica (the Siberian or Amur tiger) is found primarily in the Amur River basin in the Russian Far East region (Miguelle et al., 1999b). In Russia, tiger distribution is primarily concentrated in and around the Sikhote-Alin Mountain Range (Figure 1). Temperature and precipitation regimes of the area are characterized by a monsoon climate with large amounts of rainfall during summer months (Miasnikov, 2002). The monsoon precipitation regime is periodically disrupted by the development of ENSO-related anomalous anti-cyclones over the South China Sea which move northeastward during spring and summer of El Nino years (Wu et al., 2003). The complex topography and the convergence of two main bioregions – the East Asian coniferous-deciduous complex and the northern boreal complex – create a complex and varied landcover pattern. Within this area below the elevation of 700m, primary forests are composed of Korean pine and oak and birch broad leaf stands which are considered a typical habitat for Siberian Tigers. At elevations over 700m spruce/fir forests prevail. Primary forests are replaced by secondary oak/birch stands as a result of logging or wildland fires. The combination of environmental conditions in the Sikhote-Alin Mountains created the world's richest and most unique temperate forests with a high percentage of endemic floral and faunal species (UNESCO, 2002).

Miguelle et al. (1999b) defined four levels of spatial scale - "orders of selection" - on which habitat selection by tigers can occur. *First order of selection* refers mainly to the geographic range of the Siberian Tiger. *Second order selection* describes an individual tiger's home range (around 500km^2) and a set of habitats found within such home ranges. *Third order selection* demonstrates habitat preferences within home range. *Fourth order* incorporates individual food items. First and second order selections are driven by prey availability, population densities of which largely depend on the availability of preferred land cover. Habitat fragmentation caused by wildland fires will affect prey availability and consequently Siberian Tiger population density. Third order selection is driven by the ability of tigers to mate, guard the home range, etc. which is not likely to be affected by wildland fires as much as the first and second order of selection. This suggests that it would be most important to examine wildland fire impact on the scales of 1) home range and 2) geographic range.

Although the mapped distribution of the Siberian Tiger which was completed in 1998 (Smirnov and Miguelle, 1999) does not extend to cover the entire Sikhote-Alin Mountain Range, the entire region was included in fire danger assessment to account for potential changes in tiger distribution and the impact of neighboring areas on the fire occurrence within known areas of tiger distribution.

3. Study Rationale

Fire danger assessment, defined as "the estimation of those conditions which may lead to fire ignition or facilitate its propagation" (Chuvieco et al., 2003), is a part of a more comprehensive fire threat analysis. Solichin et al. (2003) presented a scheme for fire threat analysis mapping in West Kutai District of East Kalimantan. According to the authors, a Fire Threat Analysis map, incorporating Fire Danger Map (created through an assessment of Risk of Ignition and Potential Fire Behavior), Values at Risk, and Fire Suppression Capability, will enable fire management organizations to support fire prevention campaigns as well as successfully plan and prioritize fire suppression activities. Based on the described approach, a Preliminary Fire Threat Analysis scheme was developed with the primary focus on mapping Fire Danger for the Siberian Tiger Habitat (Figure 2). The presented Fire Danger assessment is adjusted to the conditions of the study area and includes a number of hypotheses examined within this project.

Hypothesis I. *The average monsoon climate of the study area mitigates against catastrophic fires. Therefore, wildland fires present a threat only during years of uncharacteristically dry climatic conditions.*

During the winter, low temperatures and significant accumulation of snow on the ground prevent wildland fire spread in the region making significant fire occurrence possible only during the growing season. By definition a monsoon climate is characterized by a large amount of precipitation during the high-sun period (Ritter, 2003). Therefore, during years of normal monsoon regime wildland fires should not present a significant danger to the forest cover and consequently to the Siberian Tiger. However, disruption of the monsoon regime could lead to drought and consequently to catastrophic fire events.

Hypothesis II. *Fire Danger varies significantly within the Siberian Tiger Habitat.*

The study area covers a large geographic region with complex topography, land cover, and land use patterns. According to the Fire Danger assessment scheme, all these parameters influence the Fire Danger level. Therefore, it is reasonable to expect a considerable variety in Fire Danger estimates for various regions within the study area.

Hypothesis III. *Risk of ignition can be estimated with high accuracy through area accessibility and land use patterns.*

Although fire is considered a natural process of ecosystem dynamics (Kasischke et al., 1999; Miller and Yool, 2002), a number of studies have demonstrated a high dependence of frequency of ignition on human activities (Garcia-Montero et al., 2003; Leone and Lovreglio, 2003; Solichin et al., 2003). Unlike “accessibility” which is included in all examined fire danger assessments, land use pattern has not received much attention in the literature. Based on the social study of human fire causes by Leone and Lovreglio (2003), land use patterns were included in the Preliminary Fire Danger assessment scheme.

Hypothesis IV. *There is a high likelihood of significant Siberian Tiger habitat fragmentation in the case of catastrophic fire events.*

Burned area estimates for 1998 and 1976 (WWF, 2001; Bushnell, 2002) show that during catastrophic fire events large areas of forests can be affected by fire leading to significant fragmentation of the habitat which is considered a major threat to all tiger species (Seidensticker et al., 1999a). The well-being of the Siberian Tiger depends on availability of large continuous areas of suitable habitat (Miguelle et al., 1999a; Seidensticker et al., 1999b). Therefore, if large areas of the Siberian Tiger habitat lie within a high fire danger zone, it is indicative of a potential threat to the species.

4. Data and Methodology

Due to the vast territory of the study area (over 30million hectares), complex terrain of the Sikhote-Alin Mountains, and spatial and temporal constraints of many traditional data sources, the majority of data evaluated in this project were acquired through satellite observations. The large size of the study area is suited to the use of moderate (500m) and coarse (1km) resolution remotely sensed datasets. The complete list of data sets used in this project is presented in Table 1. Different combinations of various data sources were assimilated and processed within a Geographic Information System (GIS) environment (ArcView©3.3 and ArcInfo©8.1 - ESRI), image processing environment (ENVI© 3.6 - Research Systems), Microsoft Excel©, and Microsoft Access© programs. A more detailed description of various stages of data processing is presented in the sections describing the Preliminary Fire Danger assessment scheme.

Risk of Ignition

The overall evaluation of the Risk of Ignition was based on version 4 of the active fire product from MODIS/TERRA for the period of 2001-2003 (Justice et al., 2002). The center points of 1km MODIS fire pixels were considered individual fire counts.

To estimate risk of ignition, separate fire counts were aggregated to spatially and temporally coherent fire clusters. To evaluate spatial integrity of a cluster, individual points representing the center of fire pixels were buffered to a 1km^2 area to match MODIS active fire detection resolution. An additional 1km buffer was added to allow for fire spread differences and missed observations due to potential presence of cloud cover. All fire observations falling within these overlapping areas were considered spatially coherent. Clusters were considered temporally coherent if the gap between consequent observations was less than 4 days. Clusters which did not meet the temporal coherence criteria were split according to the dates of detection. The split clusters were visually examined to ensure that the spatial coherence of the split clusters was not affected. Upon the final assignment of separate fire observations to individual fire clusters, the attribute data were processed in Microsoft Excel© and Microsoft Access© to determine the earliest date of fire detection within a cluster. This date was considered to be the ignition date and it became the primary parameter for further evaluation of Risk of Ignition.

During the analysis of the Risk of Ignition, based of the assignment of fire pixels to designated zones (*e.g.* land use zones), ignition date pixels from the same cluster were often identified within multiple zones. Because there is no other way beside the ignition day to identify likely areas of ignition, all active fire detection points with the appropriate ignition date were included in the analysis. Therefore, the sum of the number of fire clusters initiated within individual zones may exceed the total number of fire clusters detected for a particular year.

Accessibility

Under the assessment scheme adopted in this project (Figure 2), Accessibility is evaluated using population distribution and terrain data. To evaluate the terrain component of area accessibility, a measure of steepness of slope divided into 10 categories (0 – 90 degree slope) was calculated from the U.S. Geological Survey Digital Elevation Model (DEM) (USGS, 1996). To estimate the population propagation in the study area 5, 10, and 15 kilometer buffer zones were created around the GIS layers of major transportation routes (roads, major rivers, and railroads) and 5, 10, 15, and 20 kilometer buffer zones were created around human settlements.

Land Use

The Land Use classification followed the scheme suggested in the "Land Resources of Russia" (Stolbovoi, 2002). The agricultural and urban categories of Land Use were adopted form the AVHRR 1km Land Cover Classification created at the University of Maryland (UMd) (Hansen et al., 2000). Visual examination showed good correspondence between the classified areas and GIS layers (Penn State University, 2003). The protected areas were determined using Land Use classification (Stolbovoi, 2002), the World Conservation Union (IUCN, 2003) coverage, and a publication by Miguelle et al. (1999a). The additional division of protected areas by the level of legal and actual protection provided by Miguelle et al, allowed for separation of protected areas into: 1) areas of high level of protection (zapovedniks and zakazniks) and 2) areas of lower level of protection (traditional and multiple use zones).

Areas outside of agricultural, urban, and protected zones were assigned to forestry use. MODIS 500m Continuous Tree Cover Fields (Hansen et al., 2003) provides an opportunity to discriminate between disturbed and pristine forests based on the reduced percent tree cover compared to remote areas. This discrimination has an important potential as reduction in canopy closure enhances moisture evaporation and raises fuel temperature which makes these areas more susceptible to fire (Whelan, 1995). Visual examination of the MODIS 500m Continuous Tree Cover product showed that areas with lower percent tree cover were often positioned in relatively flat regions at lower elevations and therefore were more likely the result of human disturbance than elevation dependant forest succession. Areas with 60 percent or less tree cover were considered "disturbed forests". An additional 1 kilometer buffer area around those was added to account for the possible spread of the "disturbed area" effect resulting from easier accessibility, changes in microclimate and cloud formation neighbor associated with neighboring intact forests. The final Land Use product analyzed within this project consisted of the following zones: 1) agriculture/cropland; 2) urban areas; 3) disturbed forests; 4) pristine forests; 5) highly protected areas/wild lands; 6) traditional and multiple-use zones; 7) water bodies.

4.2 Potential Fire Behavior

According to the Federal Emergency Management Agency (FEMA) and U.S. Fire Administration (2003), the three most crucial factors in determining potential fire behavior are fuel, topography, and weather which is assumed to be uncharacteristically dry implying high fire danger weather conditions on the ground. Weather has a direct effect on fuel characteristics (fuel moisture, fuel temperature) and on atmospheric behavior influencing fire spread (wind, precipitation, atmospheric stability, etc.) Assuming the high danger level of atmospheric conditions, the weather parameter was combined with the fuel parameter to determine Vegetation Flammability, which estimates flammability during catastrophic fire events.

The three components of terrain are slope, aspect, and elevation. Slope and aspect have a direct effect on the physical characteristics of fire and fire behavior. However, the influence of elevation is usually expressed through changes in vegetation with altitude and therefore, changes in fuel availability and characteristics (FEMA, 2003) which is examined within this project through the Vegetation Flammability parameter.

To estimate Vegetation Flammability two products derived from the remotely sensed data were utilized in the project: 1) AVHRR 1km Land Cover product (UMd) and 2) AVHRR burned scar product for 1998 produced by the Sukachev Forest Institute (SFI), Russia (Sukhinin et al., 1999).

AVHRR burned area product was compared to burned areas digitized from fine resolution Landsat/ETM+ imagery. The AVHRR product shows high accuracy in spatial assignment of the burned scars as well as in their area estimates (Figure 3). Due to the spatial constraints on the data availability, this product was not created for the entire study area. Therefore, only the northern part of the study area was included in the analysis of the potential vegetation flammability (Figure 4), and the results of this analysis were later extrapolated to the remaining territory of the study area.

To evaluate Hypothesis I, regarding different fire threat levels during the years of regular vs. uncharacteristic climatic regime, rough estimates of burned area from the 1km buffered MODIS version 4 TERRA observations were used. As shown in Figure 5, MODIS fire pixels give a relatively good estimate of fire location and its spatial extent. This methodology gives a representative sample of burned area but tends to significantly underestimate it. However, due to the unavailability of burned area products for the entire study area between 2001 and 2003, buffered active fire pixels present a good proxy for estimating burned area.

5. Results and Discussion.

Hypothesis I suggests that catastrophic fire events are uncharacteristic for the Siberian Tiger Habitat due to the monsoon climate of the area with large amounts of precipitation during the summer months. A rough burned area estimate from MODIS active fires was calculated to determine the years of high fire activity. According to the burned area estimates, 2001 and 2002 were years of relatively low fire activity with 244,205ha and 147,760ha of burned area respectively. For 2003 this analysis estimates 477,591ha of burned area and therefore 2003 is considered a high fire activity season. A brief analysis of temporal distribution of active fires (Figure 6) showed a considerable difference in temporal distribution of fires between the years of high (2003) and low (2001, 2002) fire activity. The peak in fire occurrence during the years of low fire activity falls on the spring period which is followed by an extremely low frequency of fire occurrence during the summer. This temporal distribution of fire occurrence coincides with the precipitation regime of monsoon climate. The highest fire frequency observed in the year of high fire activity (2003) falls in July which suggests that the climatic conditions were unusually dry during the summer months. Years of known catastrophic fire events - 1976, 1988, and 2003 – are also characterized by the occurrence of El Nino events (http://vathena.arc.nasa.gov/curric/oceans/elnino/task3.html). These unusual climatic conditions lead to drought allowing the fire occurrence to continue into the summer and resulted in the explosion of wildland fire spread over this area. The author concludes that the temporal distribution of fire occurrence during high and low fire activity years supports Hypothesis I.

Analysis of frequency of fire occurrence by land cover type is of particular importance when studying the Siberian Tiger habitat. A considerable difference in frequency of fire occurrence within particular land covers was observed between the years of high and low fire activity (Figure 7). This difference proved important when compared to the distribution of land cover types within the Siberian Tiger habitat (Figure 8). The analysis determined that during low fire activity seasons of 2001 and 2002, fire frequency over the predominant land cover in tiger habitat (mixed forests) is low compared to cropland, woodland and wooded grassland. However, during high intensity fire seasons (2003) and catastrophic fire events (1998), fire frequency in evergreen needle-leaf forests, which constitute 20 percent of the Siberian Tiger habitat, increases as a function of the intensity of a given fire season. The results of this analysis support Hypothesis I by proving that during low fire activity seasons which are regulated by the monsoon regime of the area, fire does not present a significant threat to the Siberian Tiger habitat. This analysis showed that the there is a considerable difference in fire occurrence between areas of different land cover which supports Hypothesis II regarding uneven distribution of fire danger. The results also support Hypothesis IV proving that high fire activity seasons and catastrophic fire events are likely to cause significant impact on the habitat not only through a direct increase in burned area but also through a large impact of wildland fires on land covers of high importance within the Siberian Tiger habitat.

In the process of data assimilation and literature review, the Preliminary Fire Threat Analysis Scheme underwent a number of modifications to adjust the analysis to the specific conditions of the region. Additional changes were made during the data analysis prompted by the analysis findings. The final scheme for Fire Threat Analysis for the Siberian Tiger Habitat is presented in Figure 9. Five qualitative danger levels were assigned according to the results of the analysis: “very low” (VL), “low” (L), “moderate” (M), “high” (H), and “very high” (VH). The integration of risk levels for any two components was assigned according to Figure 10. This integration scheme was based on a similar scheme presented by Garcia-Montero (2003) and was expanded to include a “very low” danger level.

Risk of Ignition

The analysis of the fire ignition likelihood as a factor of proximity to major transportation routes (Table 2) showed that on average over 80 percent of all fires start within a 5km zone from major roads, railroads, and rivers, 16 percent of fires start within a 5-10km zone, 4.5 percent of fires start within a 10-15km zone and 7.8 percent of fire events start outside of the 15km zone. These results suggest that the majority of wildland fires in the region are human caused. The raw percentages were adjusted to the area occupied by individual buffer zones. This adjustment is represented by coefficient *Koef* which was calculated by the equation:

$$Koef = \frac{\text{average relative frequency of fire ignition}}{\text{percent area occupied by a zone from total area of the region}}.$$

Koef presents a measure of frequency of fire ignition per unit area and was calculated for all parameters within Risk of Ignition.

The dominance of human caused fires is also supported by the analysis of risk of fire ignition as a factor of proximity to settlements (Table 3). It shows that on average over 87 percent of all fires start within a 20 kilometer radius from the human settlements: and that the zone of the highest risk of ignition is up to 10 kilometers from the settlements where over 60 percent of all fires are ignited.

The similarities between the results of these two analyses suggested that the settlements and transportation routes could be combined to estimate population propagation within the

Accessibility component (Figure 9). The map of the risk of ignition as a factor of population propagation is presented in Figure 11.

Terrain presents the natural component of the Accessibility parameter. The results of the analysis of the risk of ignition as a factor of terrain are presented in Table 4. According to these results, levels of danger for the risk of ignition decrease with an increase in the steepness of the slope. This finding supports the premise that terrain is a significant factor determining area accessibility (Figure 12). This in turn provides supporting evidence for the dominant human causes of fire.

The map of the risk of ignition as a factor of area accessibility (Figure 13) shows that the overall risk of ignition is primarily driven by the ability of the population to propagate from the settlements through the transportation routes within the study area. Remote areas are characterized by predominantly “low” danger levels of the risk of ignition. The differences in the danger level of the remote areas are determined by the steepness of the terrain.

A similar analysis was performed to determine if the land use pattern has a significant impact on the risk of fire ignition and if so, what land use zones can be considered the most fire prone in terms of the risk of ignition. According to the results of the analysis (Table 5), there is a considerable variability in the frequency of fire ignition among different land use zones. Although the raw numbers indicate that the majority of fires are ignited within disturbed forests, the *Koef* values showed that in fact agricultural areas have by far the highest frequency of ignition per unit area. Figure 14 shows the risk of ignition as a factor of land use pattern. The analyses of the frequency of fire ignition conducted during this project demonstrated prevalence of human causes of fire ignition over the natural causes.

The results of the analyses and the Risk of Ignition Map (Figure 15) support Hypothesis III of this research regarding the possibility of obtaining good estimates of the risk of ignition through area accessibility and land use patterns. The results also suggest that the current fire regime of this area significantly differs from the expected “natural/ecological” fire regime due to a strong influence of population on fire occurrence. It is reasonable to expect that without human intervention the frequency of fire occurrence would be significantly reduced.

Potential Fire Behavior

It was previously established in this analysis that wildland fire poses a serious threat to the Siberian Tiger habitat only during uncharacteristically dry climatic conditions leading to catastrophic fire events. Therefore, potential vegetation flammability was estimated based on the land cover consumption during the catastrophic fire events of 1998. The relative distribution of burned area by land cover in the northern part of the study area is presented in Figure 16. Based on this distribution, danger levels were assigned to land cover classes and the results were extrapolated over the remaining area. According to the analysis, cropland is the most frequently burned land cover type followed by evergreen needle-leaf forests. Tigers are usually found in remote areas; consequently their habitat is rarely affected by agricultural burns. However, evergreen needle-leaf forest, which constitutes 20 percent of the habitat, is the second most flammable vegetation type in the study area. Figure 17 shows potential fire behavior danger based on vegetation flammability factor.

The effect of terrain on potential vegetation flammability was assessed through aspect and slope. Aspect determines the amount of sun exposure the vegetation and soils receive and consequently determines fuel temperature and moisture. The assignment of danger levels due to the aspect was conducted according to the following scheme (Golden Software, 2003): N, NE, NW – “very low”, E – “low”, W – “moderate”, SE – “high”, S and SW – “very high”. Slope effects fire behavior by preheating upper slopes through convective and radiant heat and through draft winds which increase fire spread capabilities (FEMA, 2003; Private Forest Management Team, 2003). Fire danger increases with the increase in slope inclination. The assignment of danger levels for the slope degree was conducted similarly to the scheme used by the National Fire Danger Rating System (County of Marin, 2002). The scheme was adjusted to five danger levels used in this project: 10 or less degree slope – “very low”, 11-30 degree slope – “low”, 31-50 degree slope – “moderate”, 51-70 degree slope – “high”, over 70 degree slope – “very high”.

The combined effect of slope and aspect on potential fire behavior is presented in Figure 18. Due to the complex terrain of the Sikhote-Alin Mountains, a large portion of the study area falls within “moderate” (20 percent of the area), “high” (22 percent of the area), and “very high” (4 percent of the area) fire danger zones. It suggests that wildland fires within fire susceptible land covers (roughly 46 percent of the territory) are likely to spread fast and become difficult to control. Approximately 41 percent of the area is within the “low” fire danger zone and 14 percent of the study area is within the “very low” danger zone area, two percent of which is occupied by water bodies. Overall, “low” and “very low” fire danger areas are found to the west of the Sikhote-Alin Mountain range and are actively exploited by the population. The “moderate”, “high”, and “very high” fire danger zones are concentrated in remote mountainous areas which are more likely to be a part of the Siberian Tiger habitat.

Figure 19 shows the Potential Fire Behavior Danger estimated by the vegetation flammability during catastrophic fire events and the impact of terrain on fire behavior. The combined effect of vegetation flammability and terrain skews the distribution of fire danger towards the larger area occupied by zones with “moderate” (23 percent), “high” (28 percent) and “very high” (9 percent) fire danger. Around 36 percent of the area is found within the “low” danger zone and only three percent is within the “very low” danger zone. Such change in the distribution of fire danger zones by the potential fire behavior is mainly explained by the fact that large areas of “moderate”, “high”, and “very high” danger zones by vegetation flammability are spread over the Sikhote-Alin Mountains which considerably enhances the danger level of fire behavior. According to this part of the analysis, over 60 percent of the region lies within a “moderate” to “very high” danger zone for fire behavior which has a potential to create a considerable threat to the Siberian Tiger habitat.

Fire Danger Map

Fire Danger Map (Figure 20) presents the final stage of this project. It was created by combining the Risk of Ignition and Potential Fire Behavior. The spatial distribution of danger levels differs between the two coverages: the higher danger levels for the Risk of Ignition are correlated with human activities while higher danger levels for the Potential Fire Behavior are spread more uniformly over the region with more significant concentrations within remote areas. Figure 21 shows distribution of area by fire danger zones. Approximately 61 percent of the entire region lies within “moderate” to “high” fire danger zones. The spatial distribution of fire danger levels is supported by the distribution of known burned areas from the catastrophic fires of 1998: the northern part of this region, where the catastrophic fires occurred, lies predominantly within “moderate” to “very high” fire danger zones.

The study area was originally selected to include all areas of potential tiger habitat. Figure 22 demonstrates the distribution of fire danger zones within the known Siberian Tiger distribution for 1998. Fire danger levels are lower within the areas of known distribution of tigers compared to the areas outside. Approximately 22 percent of known habitat is found within “very low” fire danger zone, 34 percent within “low” danger zone, 28 percent within “moderate” danger zone, 14 percent within “high” and 2 percent within “very high” danger level zones. The lower fire danger levels within the known Tiger habitat are explained by the fact that tigers are often found in areas unsuitable for economic development and with limited access for population which significantly reduces the Risk of Ignition. This situation is likely to change with either the spread of human activities into the remote areas currently occupied by tigers or with the spread of tigers outside their known distribution.

Geographic analysis shows that the distribution of various danger level zones presents a complex pattern within the known Siberian Tiger habitat. Coastal areas and central Sikhote-Alin mountains (Figure 23a) are characterized by overall higher and more uniformly distributed levels of fire danger due to the presence of highly flammable vegetation. Such uniform distribution creates favorable conditions for rapid uninterrupted fire spread over very large portions of the Tiger habitat. This indicates that the habitat faces a considerable degree of fragmentation in case of catastrophic fires. Other areas facing a high possible degree of fragmentation during a catastrophic fire event are zones of tiger/human interaction (Figure 23b). In this case “low” and “very low” fire danger areas are separated by zones of “high” and “very high” danger levels. In case of a catastrophic fire event Tiger habitat can be reduced to islands of suitable habitat too small to support the needs of either an individual tiger or a viable tiger population.

The overall analysis indicates that pristine forests of the area although susceptible to fire are not necessarily threatened by catastrophic fire events. The zones of tiger/human interface have been identified as areas of highest fire danger levels. The main effort in fire management and preventative fire measures should be concentrated within these zones. It also suggests that road construction for fire management purposes will elevate fire danger levels in Tiger habitat instead of reducing them.

6. Conclusions

Sikhote-Alin State Reserve - the largest protected area in the Russian Far East and an International Biosphere Reserve – reported a steady growth of the number of tigers within its boundaries between 1966 and 1993 (Smirnov and Miguelle, 1999). In 1998, 350 adult Siberian Tigers were found in the wild (Seidensticker et al., 1999a). It is likely that with proper protection and preservation of continuous areas of habitat proposed in the Tiger Conservation Plan (Miguelle et al., 1999a), the number of tigers will continue to grow, and the tigers will spread to occupy the majority of suitable areas within the region. Although wildland fires are considered a major threat to the Siberian Tiger (Annabell, 2001), there has been little research on the potential fire threat to the tigers (Darman, 2003).

This study focused on spatial and temporal dynamics of fire occurrence within the known and potential habitat of the Siberian Tiger. The analysis supported hypotheses examined in the course of the project. Due to the strong influence of monsoon climate over this region, large wildland fires are not likely occur on a yearly basis. However, a disruption of the monsoon climatic pattern leads to uncharacteristically dry conditions and consequently, to significant and even catastrophic fire events. The analysis of the temporal distribution of fire occurrence showed that the peak of fire occurrence during high fire activity years falls on July, while low fire activity years are characterized by a similar peak in April or May and almost complete absence of fire activity during summer.

In addition to the significant increase in the overall amount of burned area, there is a considerable difference in the type of land cover burned between years of low and high fire activity. Evergreen needle-leaf forests, barely affected by fire during low fire activity years, become highly susceptible to fire during high fire activity years. This shift in land cover consumption increases the threat to the Siberian Tiger habitat, approximately 20 percent of which is constituted by evergreen needle-leaf forests.

Hypothesis II predicted the complex pattern of various fire danger levels within the study area. Due to multiple factors influencing fire danger assessment, a great spatial extent of the region, and the complex terrain of the Sikhote-Alin Mountains, the fire danger levels within this area range from “very low” to “very high”. There has been observed an overall tendency towards lower fire danger levels over remote areas and higher danger levels over developed areas. However, there is a significant variability within those geographic zones.

A high correlation between human disturbance and frequency of fire ignition in the study area has been established with a high level of confidence. Area accessibility, often considered a major factor influencing risk of ignition, was proven highly important in this analysis. In addition to area accessibility, a significant correlation between land use patterns and risk of ignition has been established. This part of the analysis supports Hypothesis III regarding the risk of ignition assessment through area accessibility and land use pattern.

Hypothesis IV suggested the high level of fire threat to the Siberian Tiger habitat during catastrophic fire events. The conclusions regarding this hypothesis primarily depend on the extent of territory considered Siberian Tiger habitat. Although the fire danger within the Siberian Tiger distribution for 1998 is lower than that for the rest of the territory, any change in tiger distribution or human development in the area will significantly affect danger level assignment and consequently change the fire threat level to the tigers. It appears more reasonable to treat the entire study area as a potential Siberian Tiger habitat for fire danger evaluation to encompass possible changes in tiger distribution. According to this scheme, around 60 percent of the potential tiger habitat lies within the “moderate” to ”very high” fire danger zone. Consequently, the likelihood of significant modification of the Siberian Tiger habitat during catastrophic fire events is very high.

The Fire Danger Map developed in the course of this project was based on coarse and moderate resolution data. The regional scale of the map makes it a valuable source of information for fire danger assessment and fire prevention management especially within a species conservation framework. Based on the finding of the study, a number of management recommendations for fire danger reduction can be made. First, years of potentially high fire activity can be predicted by their correlation with El Nino events and meteorological observations. Second, once the likelihood of a high fire intensity season is determined temporary limitations on access to forested areas of general public need to be implemented. Third, in addition to the limited access, economic activities within forests (e.g. logging) should be minimized and managers should be alerted to implement higher levels of fire prevention techniques. Fourth, a significant effort should be put into promoting public awareness on causes of wildland fire, fire impacts and their economic, ecological, environmental and health related consequences, and fire prevention. Fifth, during low fire activity seasons preventative fuel reduction campaigns should be organized in identified areas of high danger levels for potential fire behavior found in the proximity of areas with high danger levels for the risk of ignition.

Future Research

Fire Danger assessment methodology developed within this project can be used as a tool for wildlife conservation, biodiversity management, and management of many other ecological and economic resources. Although this project focused on a specific region, the methodology can be easily adjusted to meet the requirements of a particular area. Evaluation of the utility of this product by regional land and conservation managers is crucial for its future development.

Presently the analysis is restricted to three years of MODIS fire observations. Additional years of data will provide the necessary supporting or disproving evidence to the hypotheses and conclusions introduced in this project. Incorporating new and improved datasets will reduce the uncertainties in the data and outcome of the analysis.

It is necessary to develop further and automate the technique for fire clustering and fire spread analysis. Clustering methodology sensitive to the regional specifics can be developed based on the burned area products and hotspot locations. Burned area analysis can also enhance the ability to estimate potential fire damage.

The Fire Danger Map developed in the course of this project is a static representation of fire danger based on the yearly assimilation of fire related data. A brief temporal analysis of fire occurrence within this project has demonstrated a necessity for dynamic assessment and representation of fire danger based on the temporal patterns of fire distribution and ignition during the fire season. MODIS burned area products will be a critical part of future analyses.

There is a need for the development of a consistent Land Use product. As it has been established in this project, land use patterns significantly affect risk of ignition. The Land Use coverage combined for this analysis represented the best approximation available to the author. The development of a consistent product could potentially enhance the ability to estimate fire risk for the area.

Fire Danger assessment is a part of a more comprehensive Fire Threat Analysis. To estimate a threat posed by wildland fires to the Siberian Tiger, more parameters need to be included in the analysis. Values at Risk and Recovery Potential are heavily weighted within the Fire Threat Analysis. Values at Risk include an evaluation of a direct effect of wildland fires on Siberian Tiger population dynamics, development of a Map of Habitat Use Preference for the Siberian Tiger, and a similar map for impact on the Tiger's prey. The Habitat Recovery Potential may be evaluated though the fire activity and burn severity, and *in-situ* and satellite monitoring of vegetation re-growth, habitat rehabilitation, and forest succession patterns.

A set of Fire Threat Analysis scenarios based on a number of projected climate change outcomes from climate modeling coupled with land use projection scenarios will be evaluated as the final step of the future research. The projected fire threat will serve as a possible basis for the development of fire management strategies in terms of the Siberian Tiger conservation plan.

7. Acknowledgements

The author would like to thank Dr. Christopher Justice and Dr. Ivan Csiszar of the University of Maryland, College Park, for the ongoing support, encouragement, and discussions.

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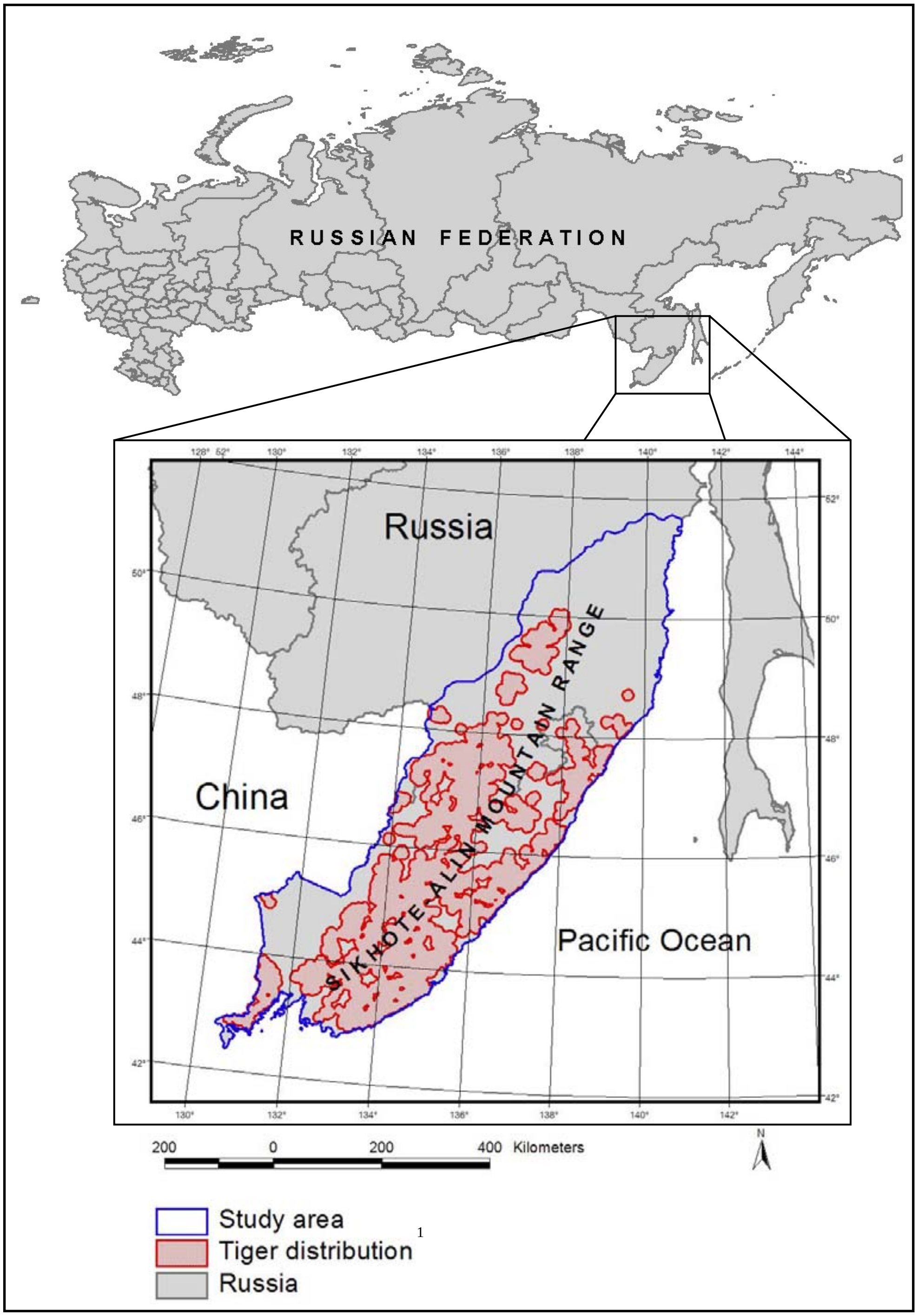
Figures.

Figure 1. Extent of study area.



[1] – **Miguelle et al., 1999b**

Figure 2. Preliminary Fire Threat Analysis Scheme.

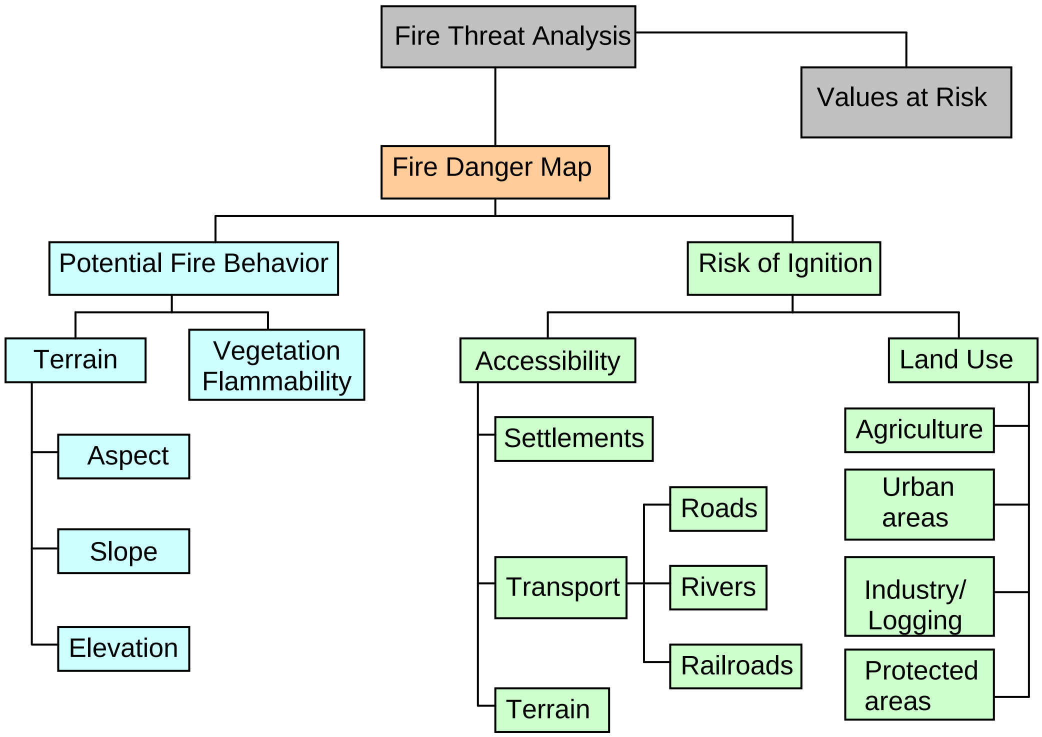


Figure 3. Validation results for AVHRR burned scar product (SFI).

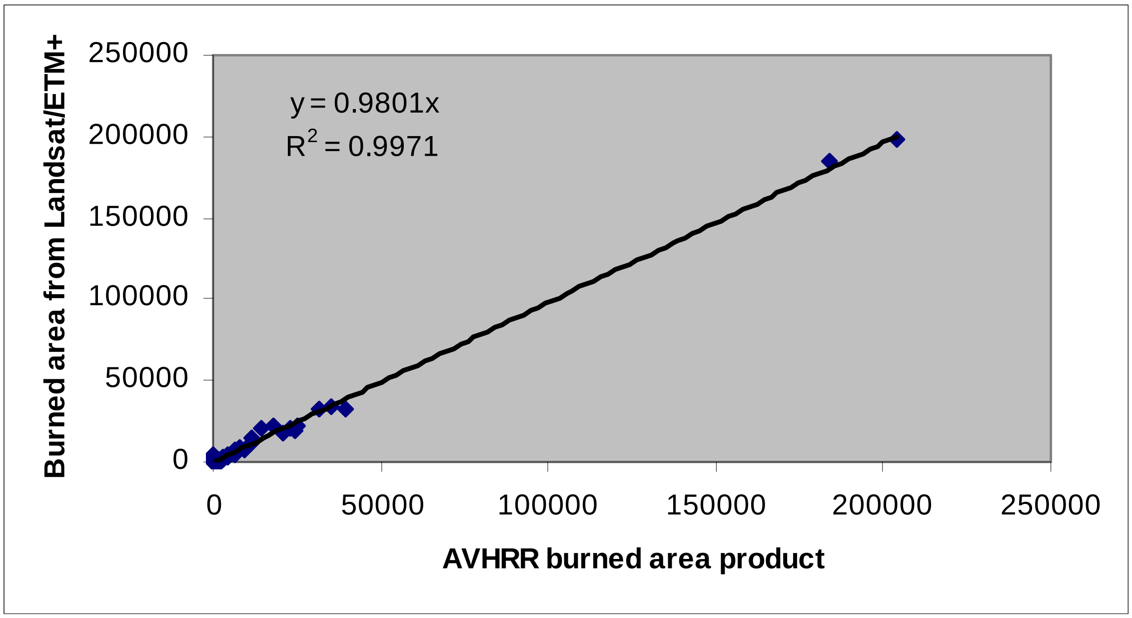


Figure 4. The extent of the AVHRR burned scar product (SFI) within the study area.

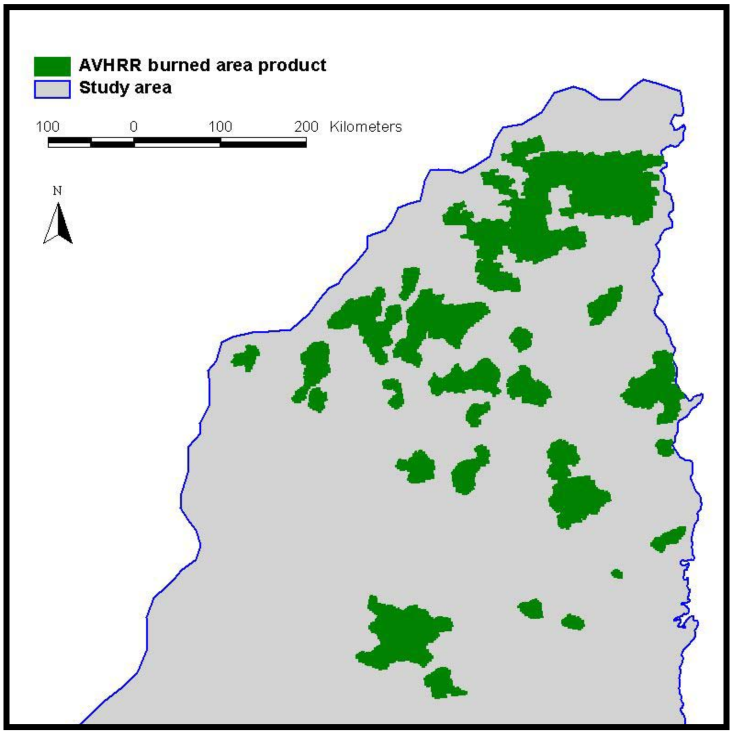
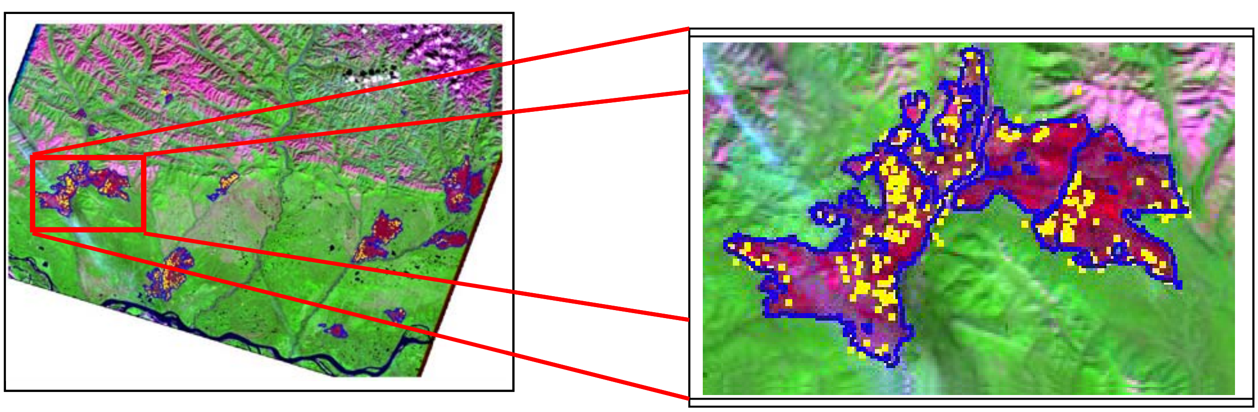
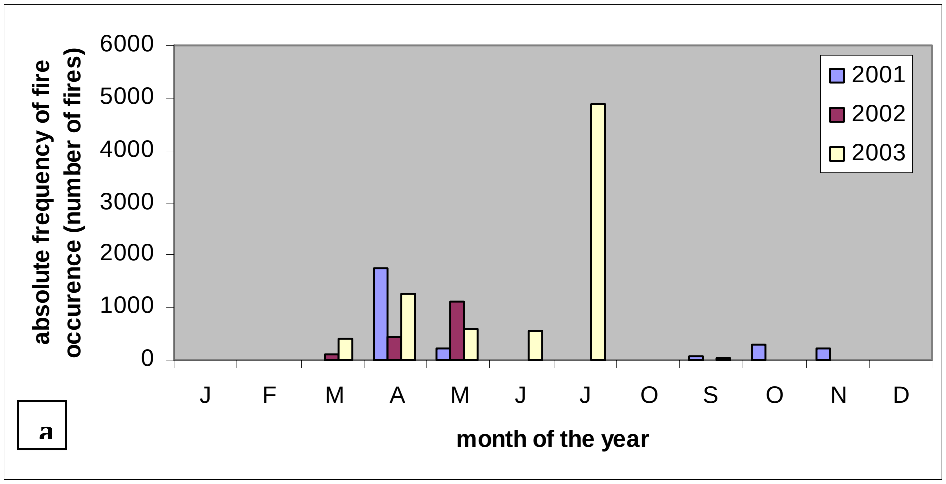


Figure 5. MODIS active fires product for Landsat/ETM+ scene path 122 row 15 from 08/16/2001.



Burned scar from ETM+ MODIS active fires product

Figure 6. Frequency of fire occurrence by year for 2001-2003: a) absolute frequency; b) relative frequency.



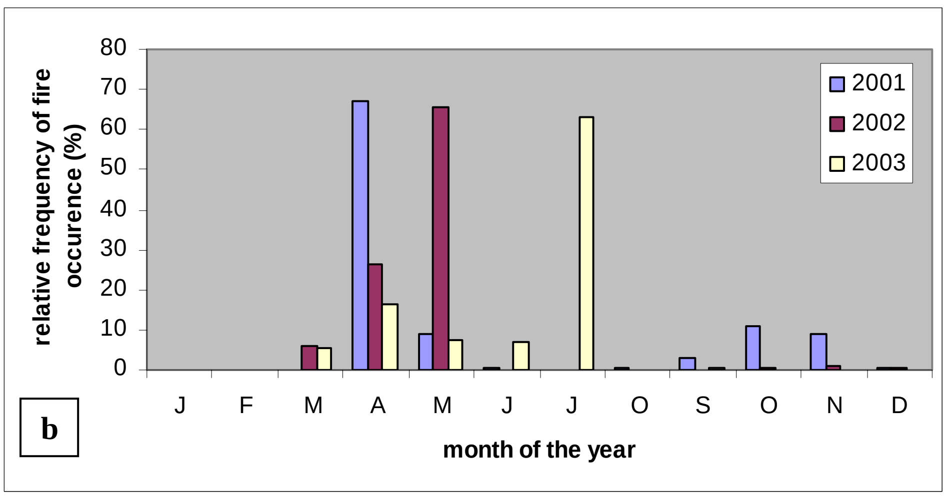
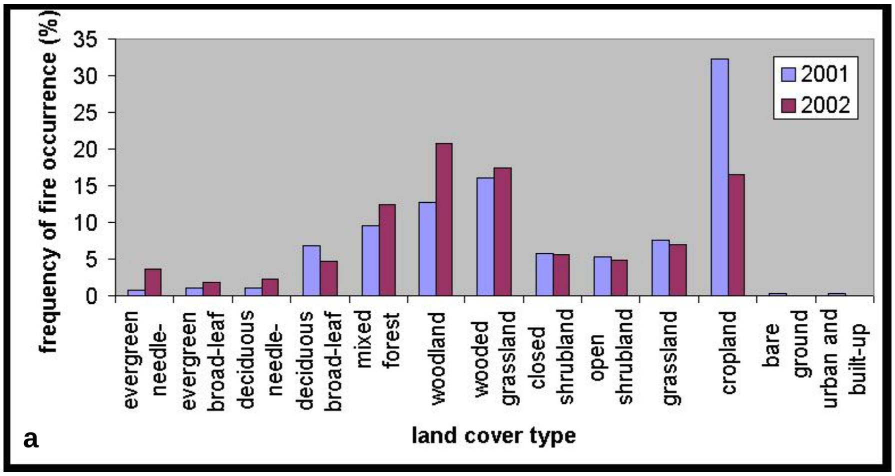


Figure 7. Frequency of fire occurrence by land cover during a) low and b) high fire intensity seasons.



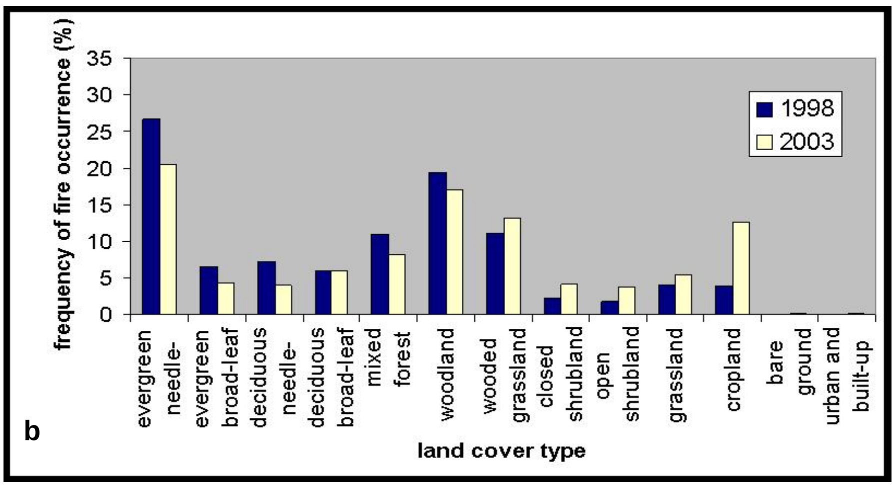


Figure 8. Land cover types within the known distribution of the Siberian Tiger

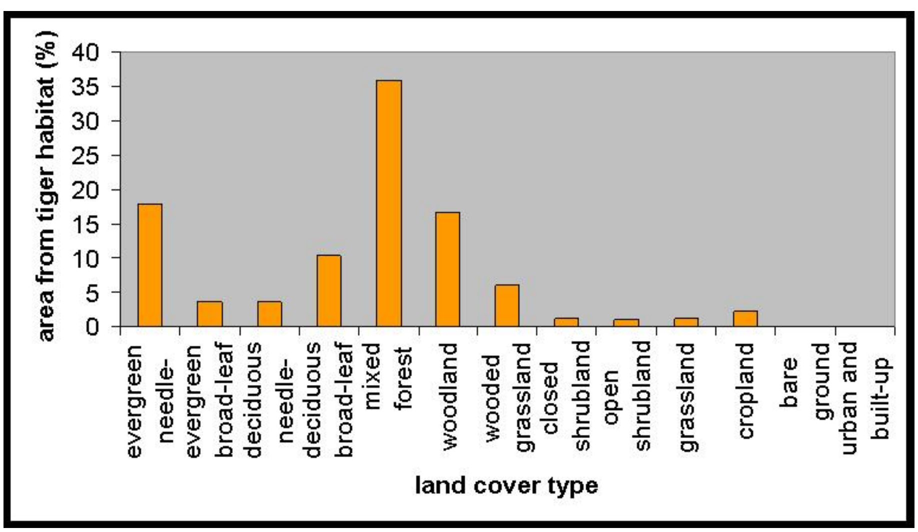


Figure 9. Final Fire Threat Analysis Scheme for the Siberian Tiger Habitat

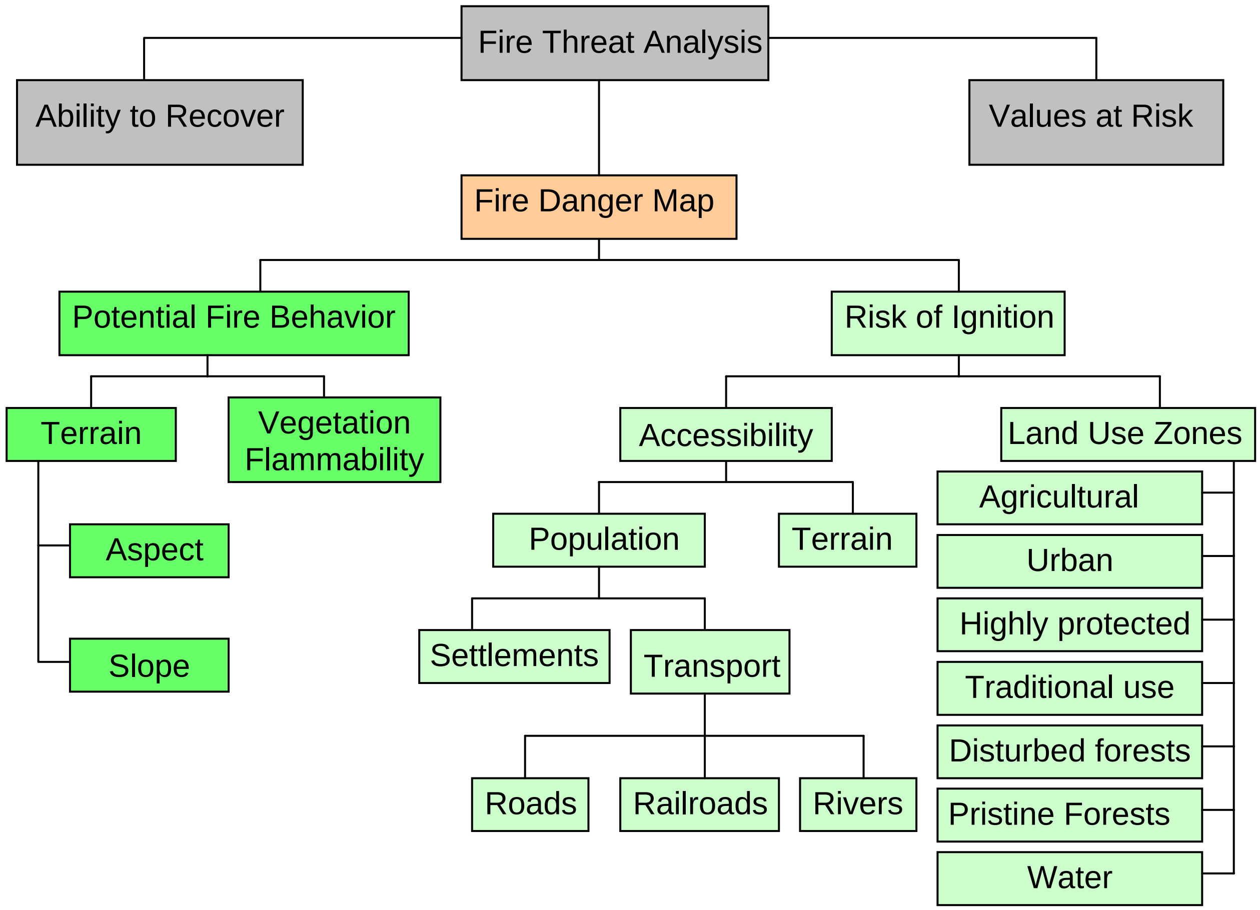


Figure 10. Assignment of qualitative risk levels and their integration for any 2 components

Component A	**Component B**				
	VL	**L**	**M**	**H**	**VH**
VL	**VL**	**VL**	**L**	**M**	**M**
L	**VL**	**L**	**L**	**M**	**H**
M	**L**	**L**	**M**	**H**	**H**
H	**M**	**M**	**H**	**VH**	**VH**
VH	**M**	**H**	**H**	**VH**	**VH**

Figure 11. Risk of ignition as a factor of population propagation

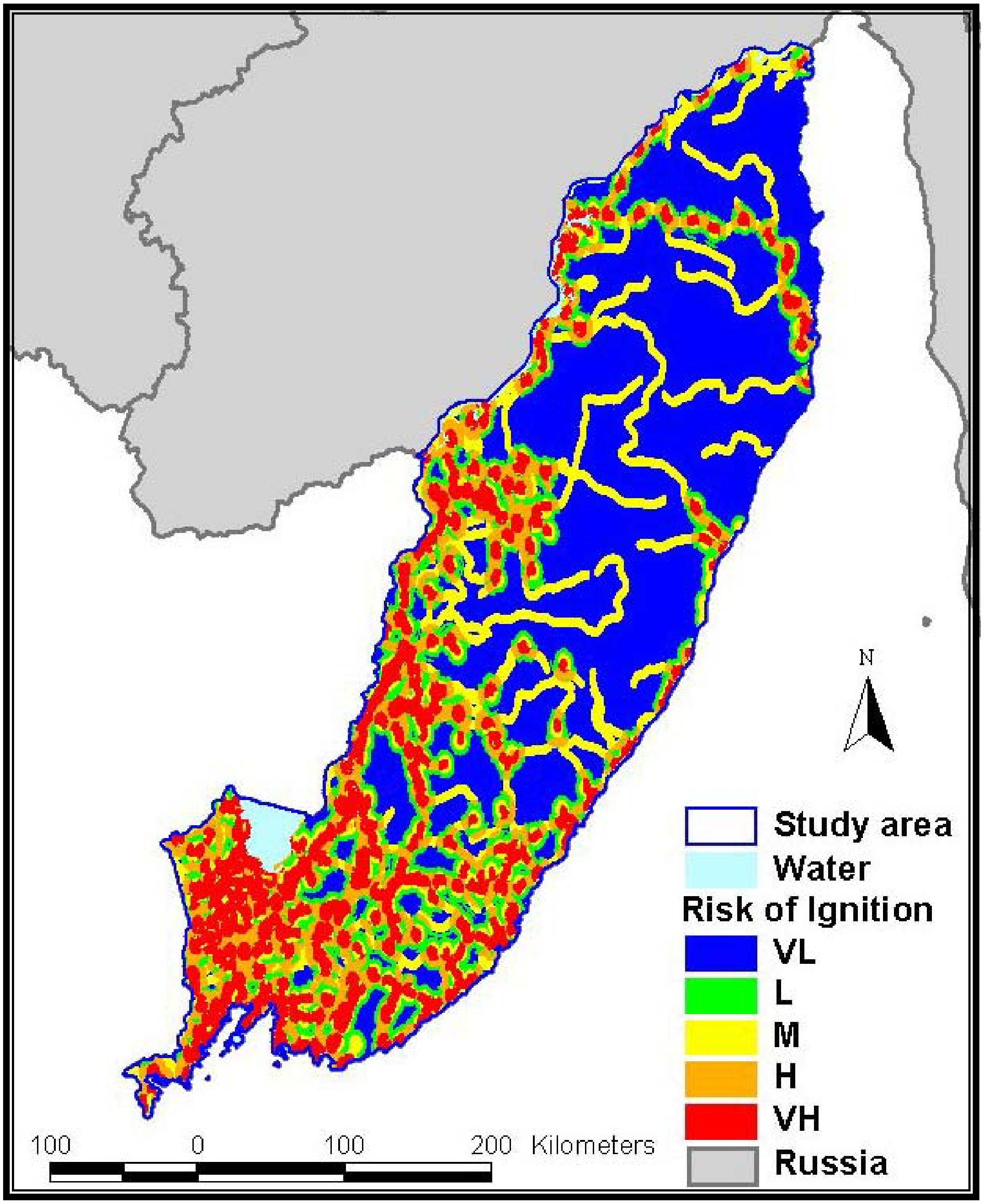


Figure 12. Risk of Ignition as a factor of terrain

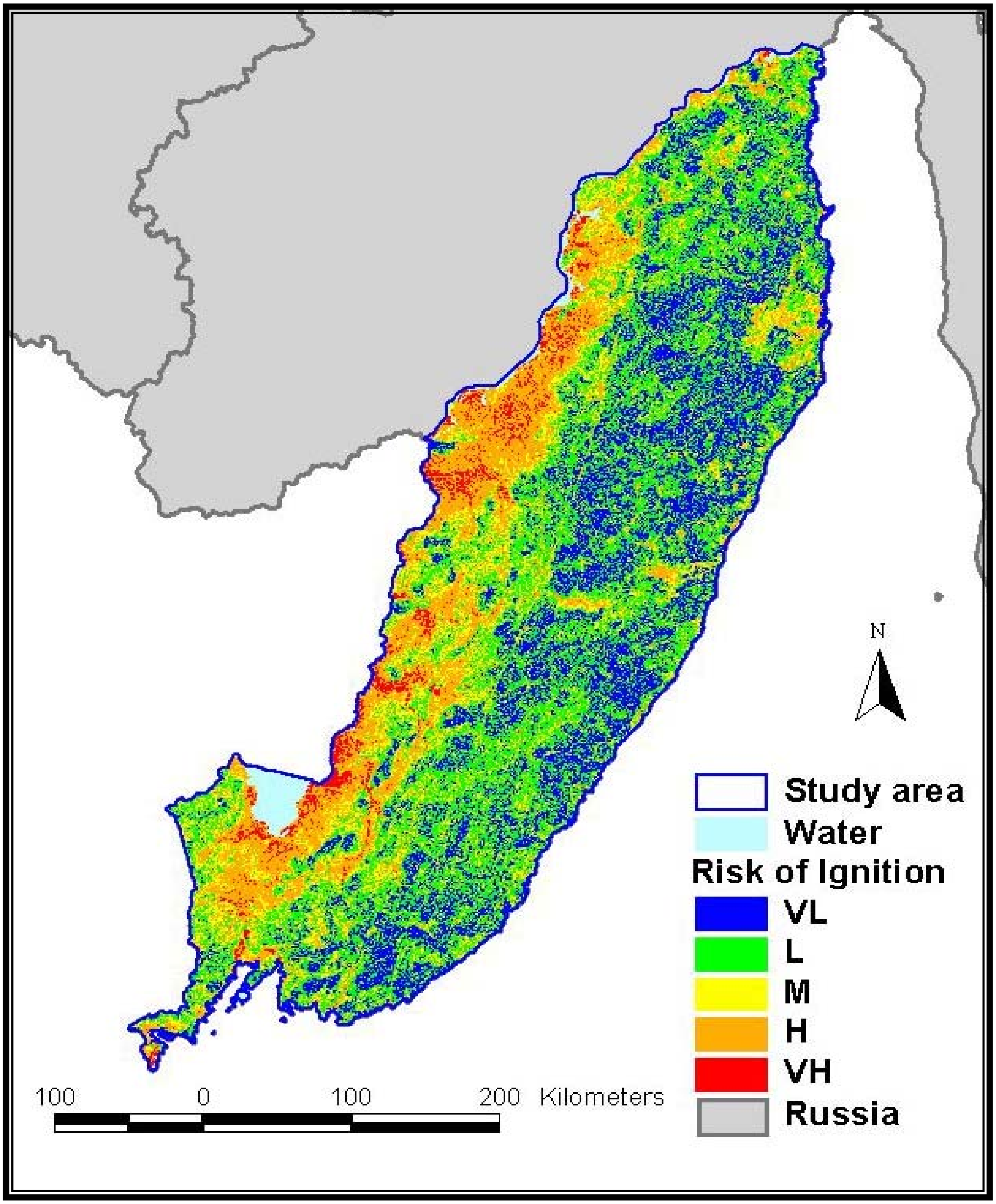


Figure 13. Risk of Ignition as a factor of area accessibility

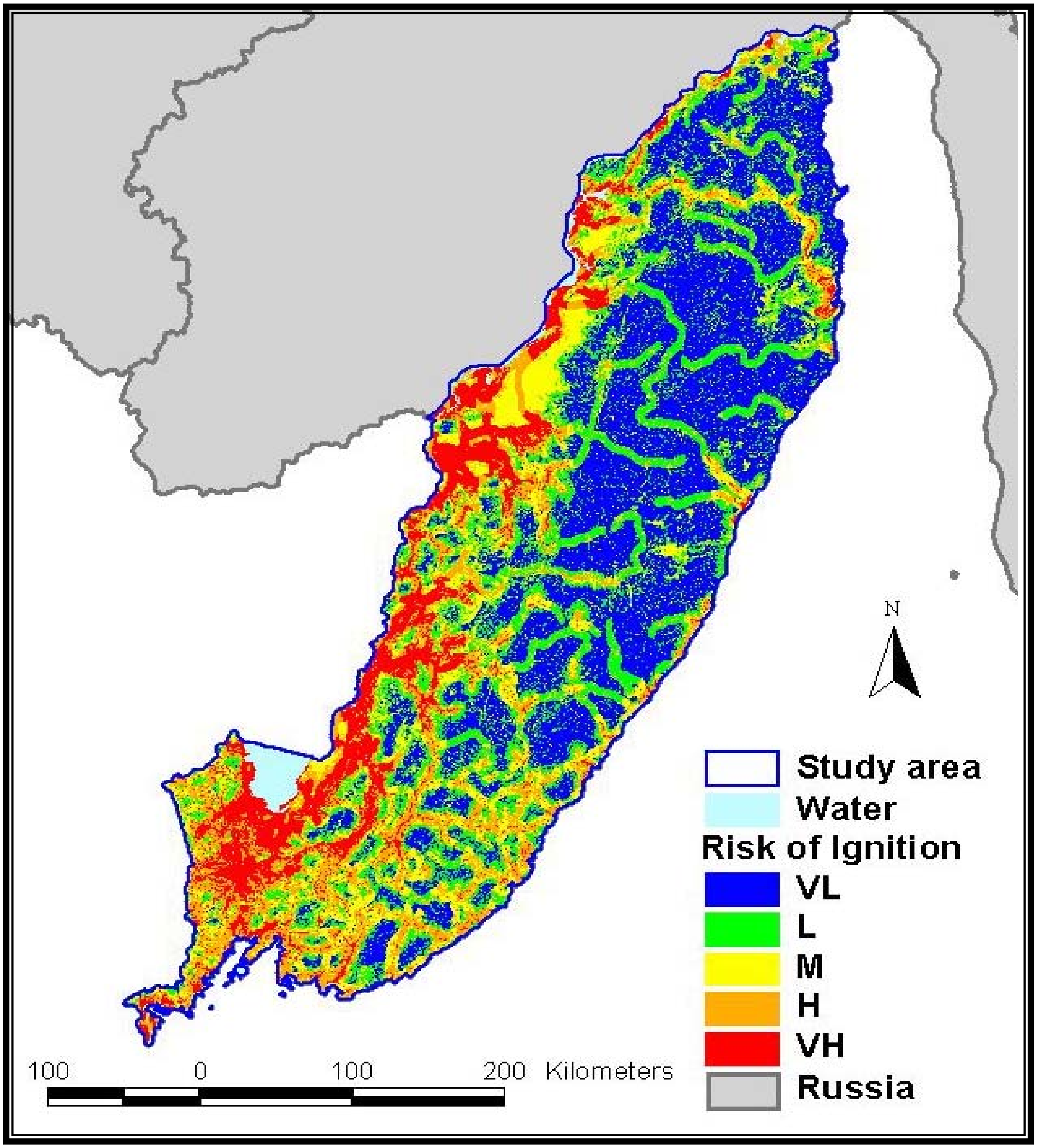


Figure 14. Risk of Ignition by land use zones

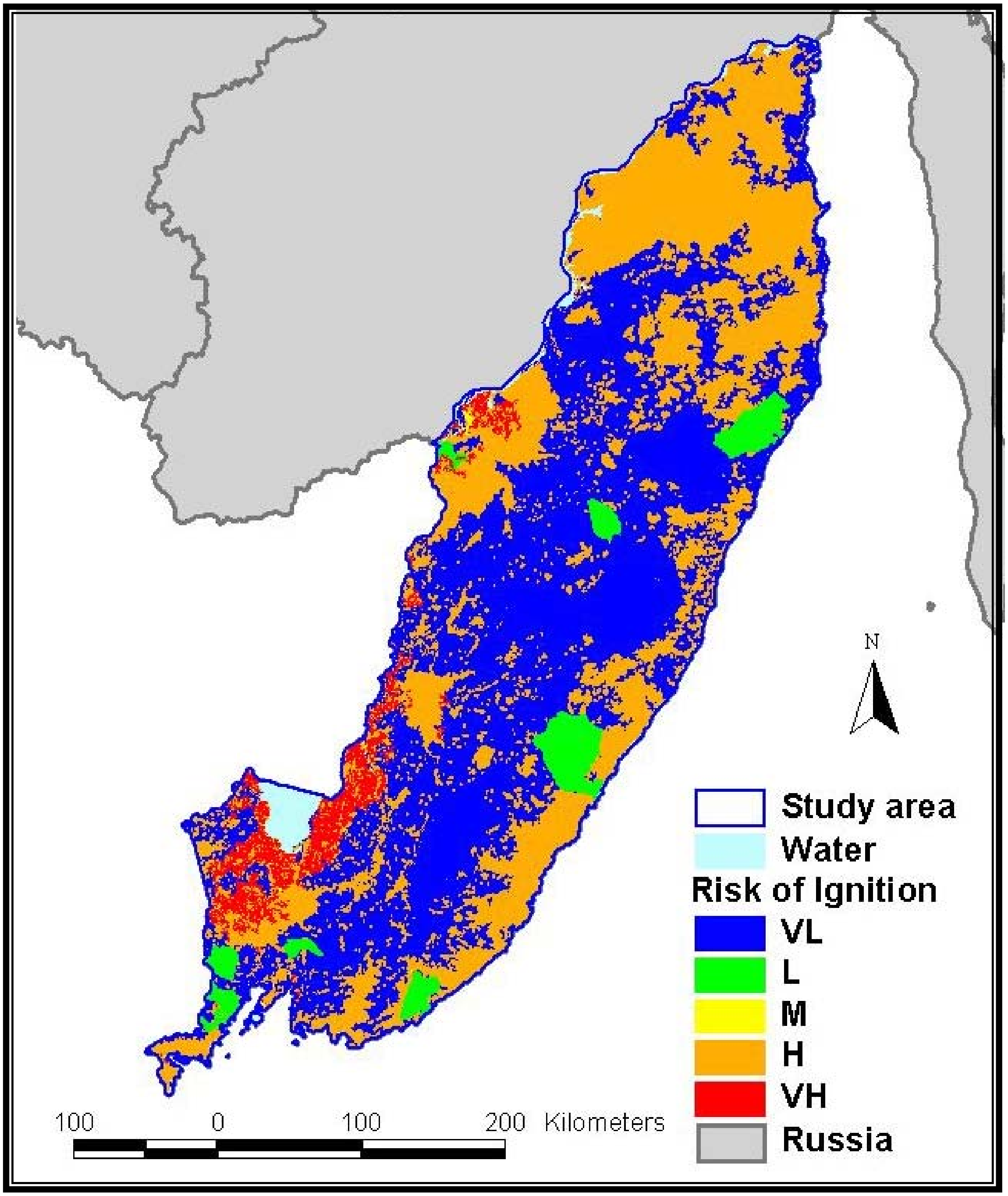


Figure 15. Risk of Ignition Map

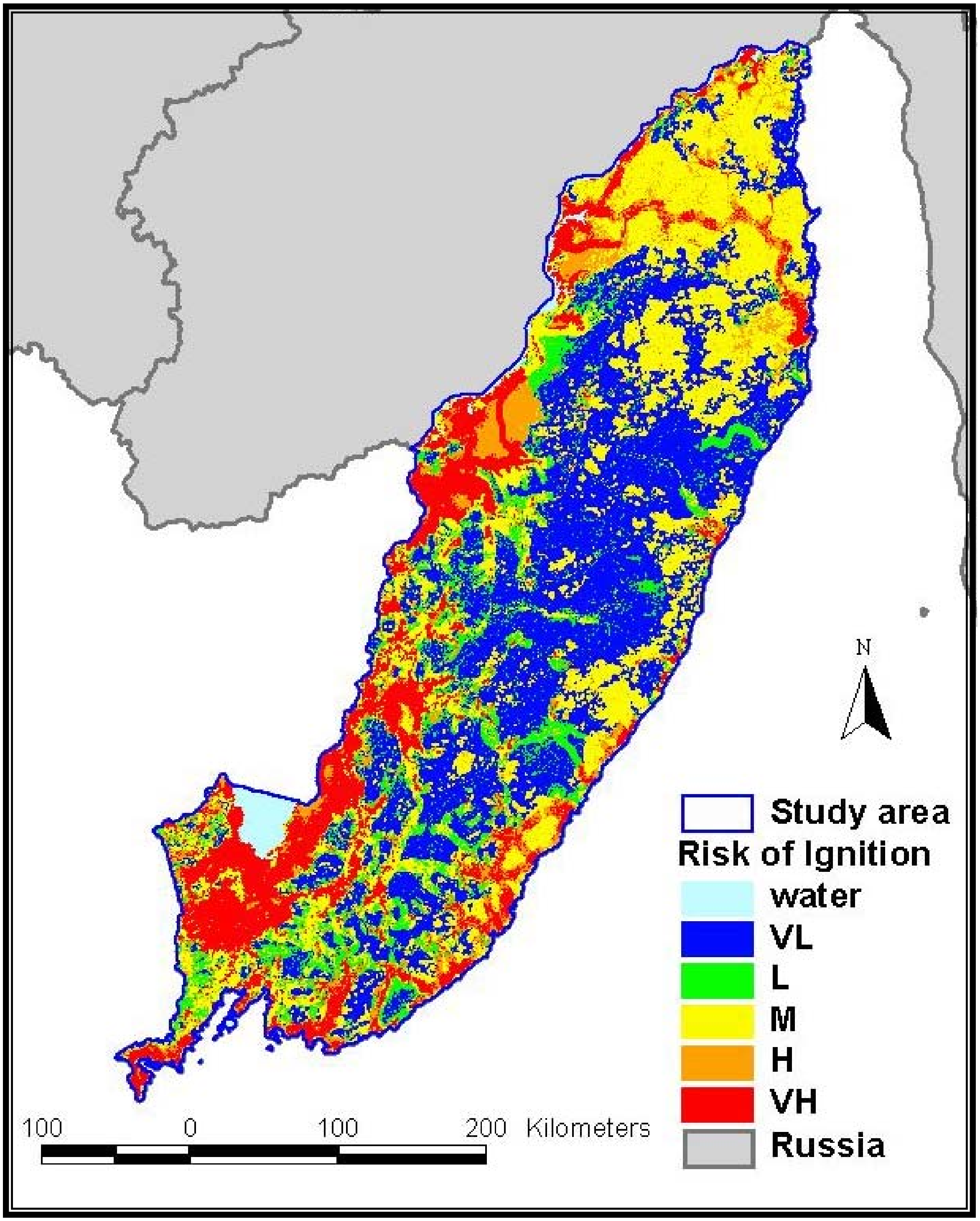


Figure 16. Land cover consumption during 1998 fire season

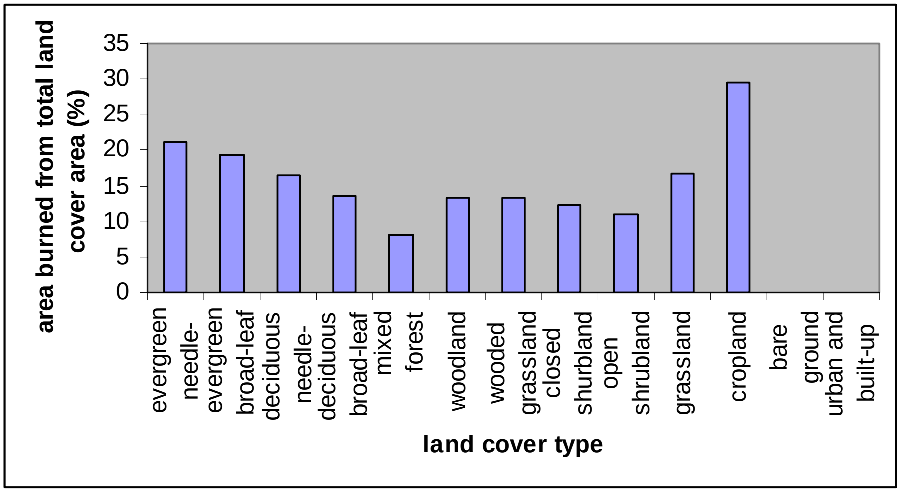


Figure 17. Vegetation Flammability Map

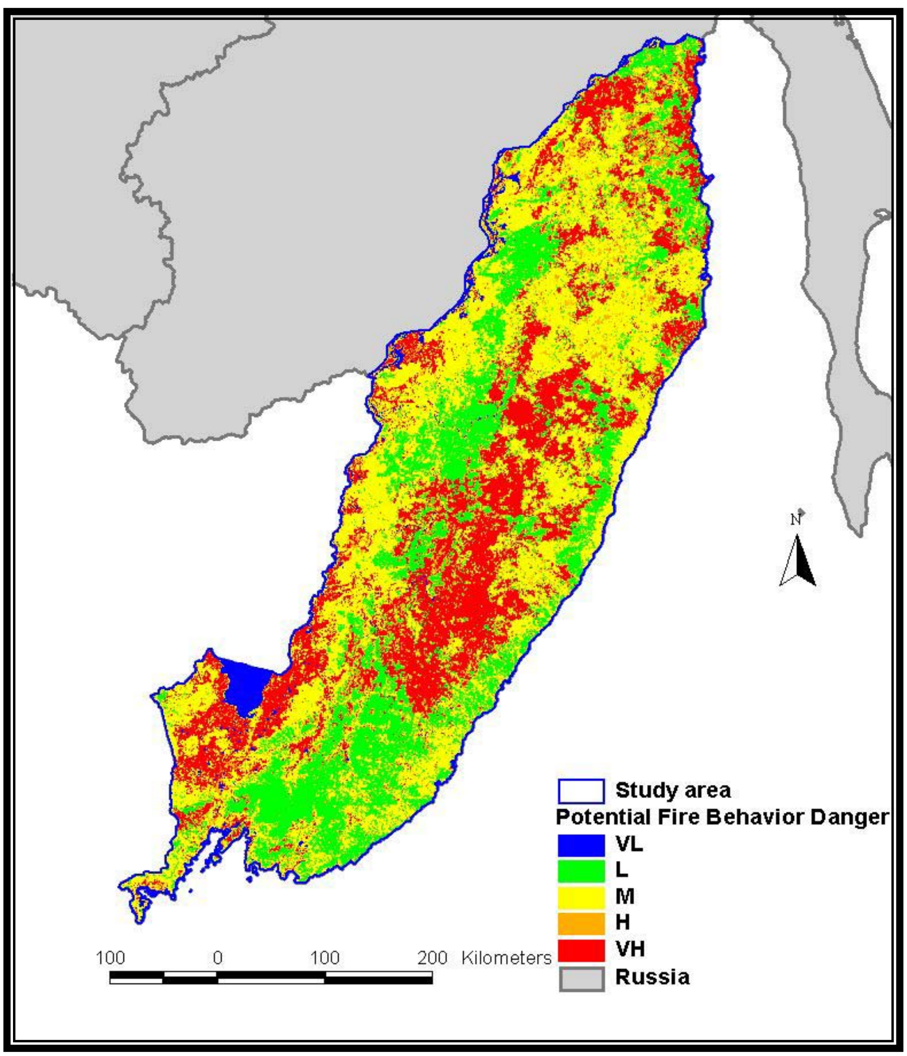


Figure 18. Potential Fire Behavior as a factor of terrain

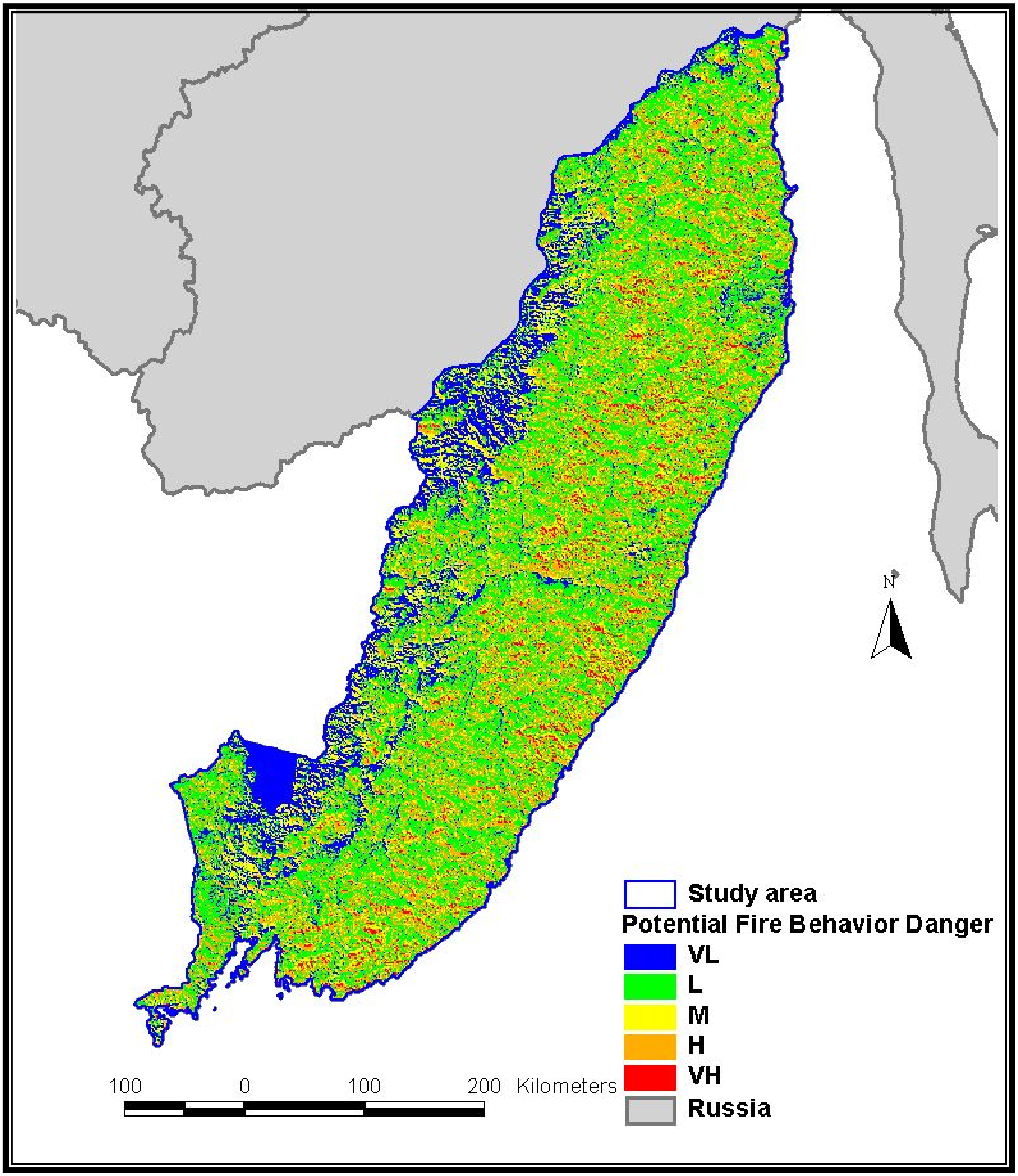


Figure 19. Potential Fire Behavior Danger

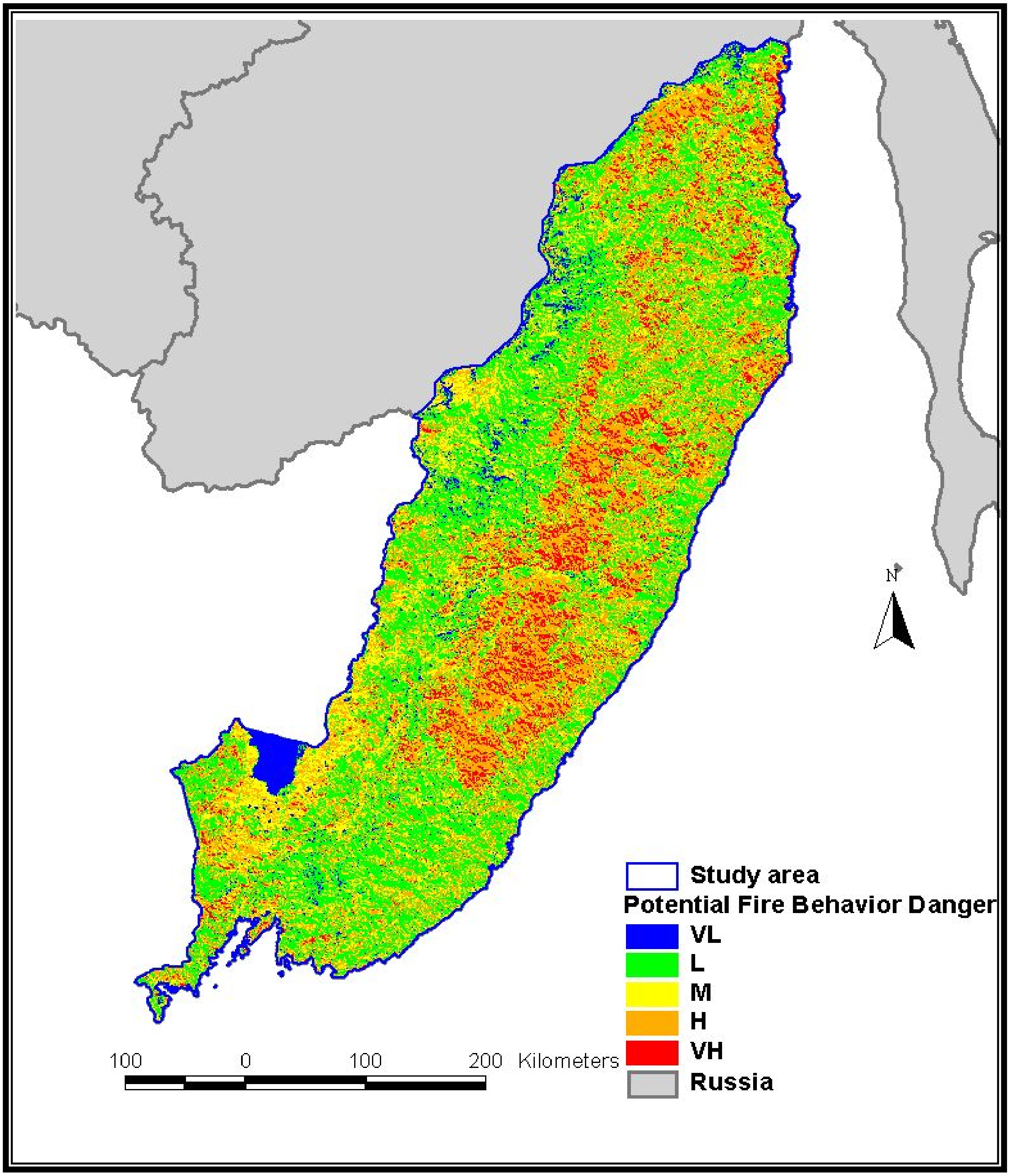


Figure 20. Fire Danger Map

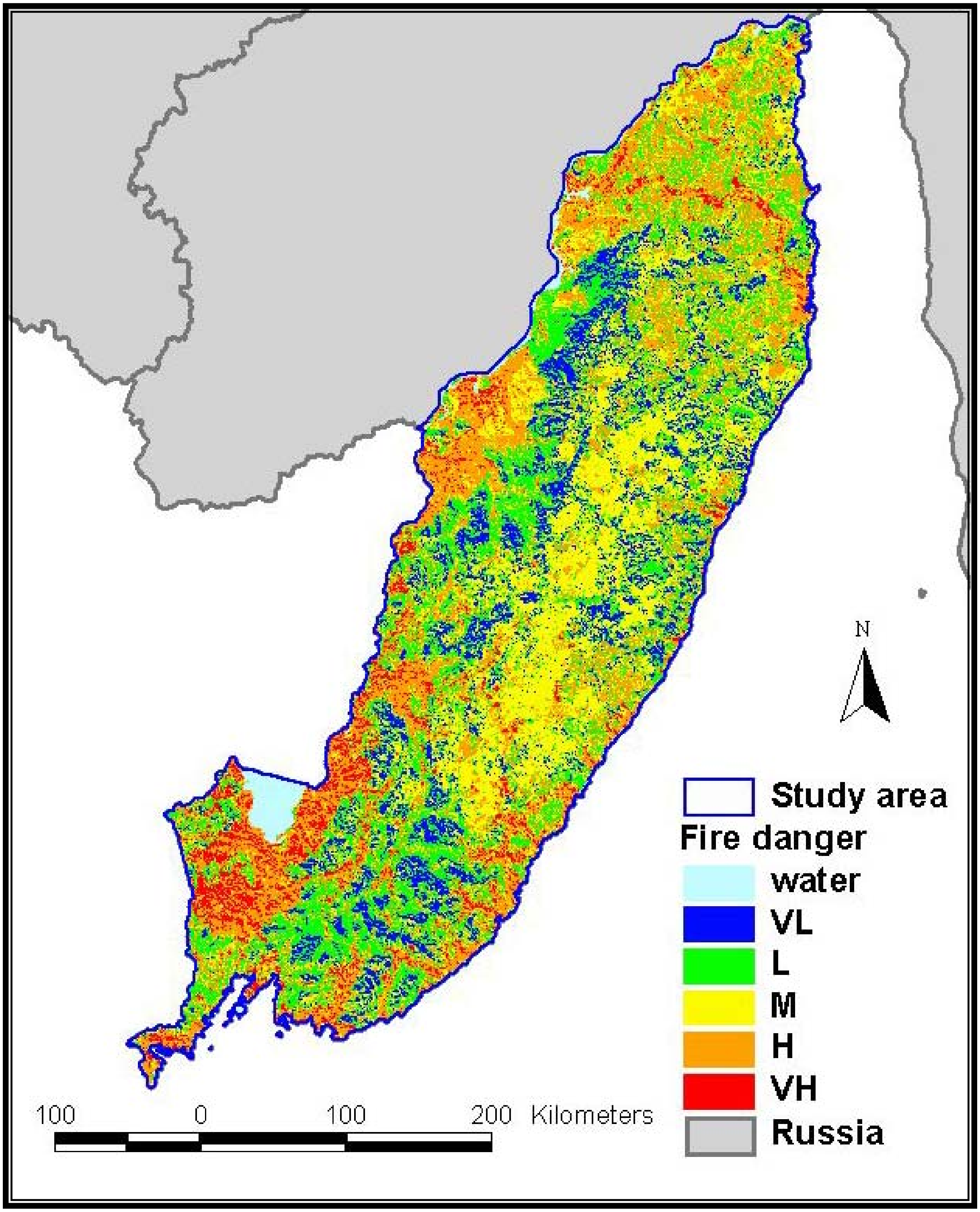


Figure 21. Distribution of area by fire danger zones within the study area

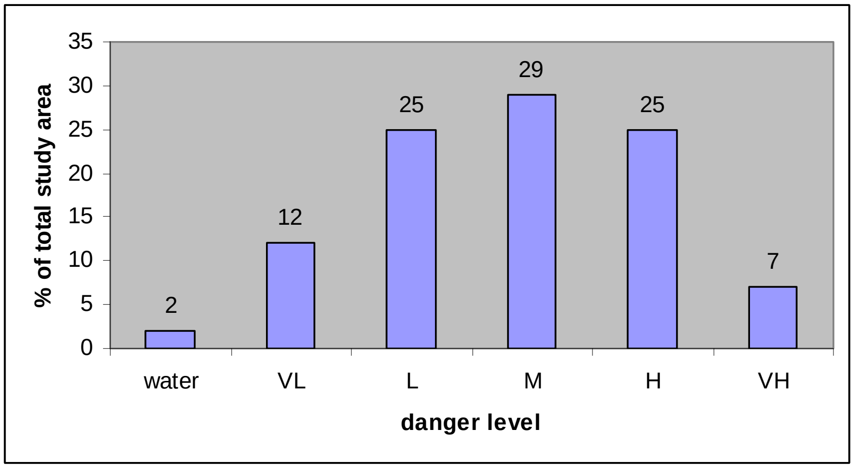


Figure 22. Fire Danger within the known distribution of the Siberian Tiger

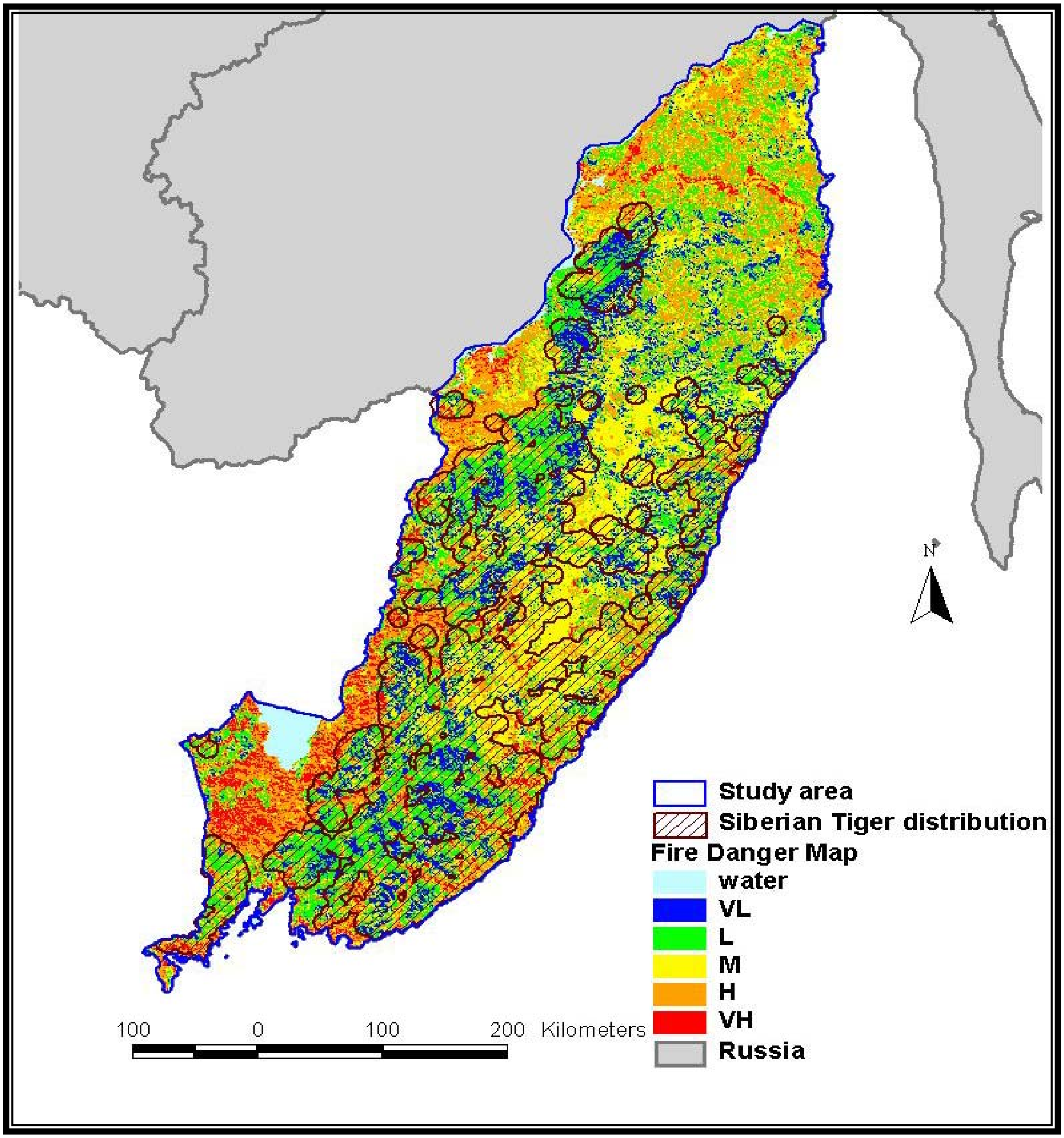
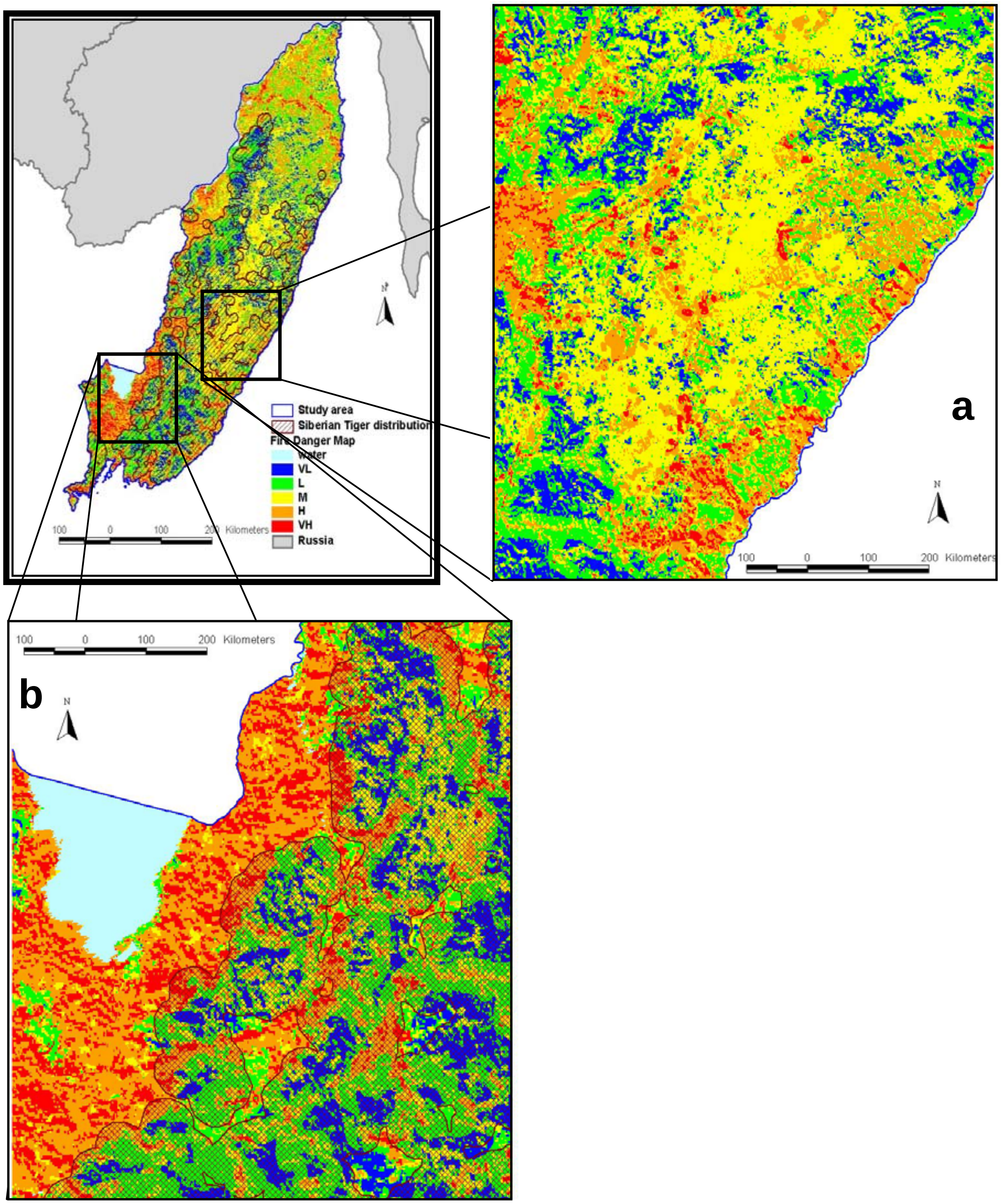


Figure 23. Areas of potentially high fragmentation in the case of a catastrophic fire event within the known distribution of the SiberianTiger.



Tables.

Table 1. Data sets used in the project.

Data Set	Resolution/Scale	Source	Distributor	References
GIS coverages of major roads, rivers, railroads, and settlements	1;1,000,000	Digital Chart of the World	Penn State University Map Room	(Penn State University, 2003)
GTOPO30 DEM	30sec arcs (1km)	USGS	LPDAAC	(USGS, 1996)
MODIS active fires (v 004)	1km	Goddard Space Flight Center	MODIS fire team	n/a
GIS land use and land cover/species coverages	varies	Land Resources of Russia	CD-Rom (IISAS and RAS)	(Stolbovoi and McCallum, 2002)
AVHRR 1km Land Cover Classification, Umd	1km	University of Maryland	Global Land Cover Facility[1]	(Hansen et al., 2000)
World Protected Areas	unknown	World Conservation Union (IUCN)	World Database on Protected Areas	(IUCN, 2003)
Protected Areas	unknown	A Habitat Protection Plan for the Amur Tiger	n/a	(Miguelle et al., 1999a)
MODIS 500m Continuous Tree Cover Fields	500m	University of Maryland	Global Land Cover Facility	(Hansen et al., 2003)
AVHRR burn scar product	1.1km	Sukachev Forest Institute, Russia	CD-Rom (SFI, Russia)	(Sukhinin et al., 1999)
Siberian Tiger distribution in 1998	unknnown	Population Dynamics of the Amur Tiger	n/a	(Smirnov and Miguelle, 1999)

Notes:
[1] – Global Land Cover Facility, University of Maryland (http://glcf.umiacs.umd.edu/index.shtml)

Table 2. Risk of Ignition by transportation routes

year	2001	2002	2003	average	koef	danger level
# in 5km zone	895	712	900			
# in 5-10km zone	154	153	195			
#in 10-15km zone	24	35	87			
total # in buffers	1022	846	1129			
total # outside buffers	23	30	108			
% in 5km zone	85.81	81.19	73.41	**80.14**	**1.94**	**VH**
% in 5-10km zone	14.77	17.45	15.91	**16.04**	**0.75**	**L**
% in 10-15km zone	2.30	3.99	7.10	**4.46**	**0.34**	**VL**
total % in buffers	97.99	96.47	92.09	**95.51**		
total % outside buffers	2.21	3.42	8.81	**4.81**	**0.20**	**VL**
total # of clusters	1043	877	1226			

Table 3. Risk of Ignition by distance from human settlements

year	2001	2002	2003	average	koef	danger level
# in 5km zone	300	202	317			
# in 5-10km zone	485	382	457			
# in 10-15km zone	213	189	229			
# in 15-20km zone	81	78	83			
total # in buffers	978	782	974			
total # outside buffers	74	111	257			
% in 5km zone	28.76	23.03	25.86	**25.88**	**3.56**	**VH**
% in 5-10km zone	46.50	43.56	37.28	**42.44**	**2.68**	**H**
% in 10-15km zone	20.42	21.55	18.68	**20.22**	**1.38**	**M**
% in 15-20km zone	7.77	8.89	6.77	**7.81**	**0.69**	**L**
total % in buffers	93.77	89.17	79.45	**87.46**		
total % outside buffers	7.09	12.66	20.96	**13.57**	**0.27**	**VL**
total # of clusters	1043	877	1226			

Table 4. Risk of Ignition by terrain

Slope	# in 2001	# in 2002	# in 2003	% in 2001	% in 2002	% in 2003	average	Koef	danger level
flat	174	133	181	16.68	15.17	14.76	**15.54**	**3.70**	**VH**
10%	618	490	671	59.25	55.87	54.73	**56.62**	**2.81**	**H**
20%	264	260	276	25.31	29.65	22.51	**25.82**	**1.45**	**M**
30%	147	148	189	14.09	16.88	15.42	**15.46**	**0.87**	**L**
40%	96	77	161	9.20	8.78	13.13	**10.37**	**0.61**	**L**
50%	34	46	102	3.26	5.25	8.32	**5.61**	**0.42**	**VL**
60%	11	15	67	1.05	1.71	5.46	**2.74**	**0.37**	**VL**
70%	1	2	21	0.10	0.23	1.71	**0.68**	**0.42**	**VL**
over 70%	0	0	0	0.00	0.00	0.00	**0.00**	**0.00**	**VL**

Table 5. Risk of Ignition by Land Use zones

Land Use Zone	agricultural	highly protected	disturbed forests	pristine forests	traditional use	urban
# in 2001	333	11	586	200	18	3
% in 2001	31.93	1.05	56.18	19.18	1.73	0.29
# in 2002	138	14	570	167	47	0
% in 2002	15.74	1.60	64.99	19.04	5.36	0.00
# in 2003	297	44	729	203	65	2
% in 2003	24.23	3.59	59.46	16.56	5.30	0.16
average	23.96	2.08	60.21	18.26	4.13	0.15
% area occupied by zone	4.25	4.11	40.23	38.11	10.73	0.10
Koef	**5.64**	**0.51**	**1.50**	**0.48**	**0.38**	**1.49**
danger level	**VH**	**L**	**H**	**VL**	**VL**	**M**