USING THE ECOSYSTEM SERVICE VALUE OF HABITAT AREAS FOR WILDLIFE CONSERVATION:
IMPLICATIONS OF CARBON-RICH PEATSWAMP FORESTS FOR THE BORNEAN ORANG-UTAN, *Pongo pygmaeus*

by

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Abstract

Forest fragmentation and degradation of lowland tropical peatswamp forests in Borneo pose a serious threat to the endangered Bornean orang-utan, whose decreasing population trends are attributed primarily to habitat loss. The orang-utan is projected to be extinct by 2020 unless existing populations can be connected and new conservation areas established, which is not currently economically viable. However, peatswamp forests, on which orang-utans can be found at their greatest densities, have a large capacity for carbon sequestration and storage and, thus, a high potential value on the carbon market. Unfortunately, as these wetlands are being deforested, drained, and burned for development, the peat soil is decomposing, emitting CO_2 into the atmosphere, and impacting global climate change. This project is a spatially explicit analysis of an area of fragmented peatswamp forest in Central Kalimantan, Indonesia that explores how the conservation targets of ape preservation and carbon sequestration and storage can be mutually satisfied through land management strategies. First, I prioritized intact peatswamp forest patches for conservation based on orang-utan presence and patch geometry metrics. To do this, I surveyed line transects in the study area, Block C of the Former Mega Rice Project, for orang-utan sleeping nests and produced a regional density estimate of 2.517 individuals / km^2. I identified patches greater than 350 ha from Landsat 7 TM data and then calculated the number of individuals and patch geometry metrics for each patch. I found the total population on Block C to be 2,161 individuals, only 1,146 of which are located in forest fragments with a population size large enough to be considered viable. I generated a model of habitat suitability for the orang-utan using maximum entropy methods. Then, I proposed corridors through degraded areas between the six priority patches of intact forest using least-cost path methods. The corridors included areas of high habitat suitability and also areas of high carbon value, and would increase the viable population size of orang-utans to 1,788 individuals. This project demonstrates how the incentive of carbon financing can make possible wildlife protection strategies, and how we might begin to use spatial planning to maximize biodiversity and ecosystem service benefits on the landscape.

Keywords: Borneo, carbon market, conservation planning, habitat corridor, orang-utan, peat

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Abbreviations

CDM	Clean Development Mechanism
CIMTROP	Centre for International Cooperation in the Sustainable Management of Tropical Peatland
COP	Conference of the Parties
LULC	Land Use / Land Cover
OuTROP	Orang-utan Tropical Peatland Project
PSF	Peatswamp Forest
REDD	Reduced Emissions from avoided Degradation and Deforestation
UNFCC	United Nations Framework Convention on Climate Change

Introduction

The lowland peatswamp forests in Kalimantan, Indonesia, provide invaluable ecosystem services to the nearby human populations, as they buffer saltwater intrusion (Boehm and Siegert, 1999), prevent flooding problems downstream, and resist large-scale fires (Yule, 2010). Additionally, of great importance to the international community, peatlands have a large capacity for belowground carbon sequestration and storage and, thus, a high potential to slow global climate change. They are also rich in endemic flora and fauna (Yule, 2010). However, peatland areas all over Southeast Asia are being degraded and fragmented due, in large part, to the development of oil palm and timber plantations, agriculture, and logging (Hoojier et al. 2006). The lowland areas are being targeted for agricultural development primarily because they are more accessible and thus easier to cultivate than mountainous areas. In recent years, large, monoculture oil palm (*Elaeis guineensis*) plantations in particular have expanded rapidly in response to international demand for the various products that are manufactured from the palm's oil. In fact, between 1984 and 2003, the area planted with oil palm on Borneo increased from 2,000 km^2 to 27,000 km^2, about 10,000 km^2 of which is located in Kalimantan (Ancrenaz et al., 2008).

Peatswamp Forest Degradation and The Orang-utan

As these lowland peatswamp forest fragments become sparser and more fragmented, species that depend on these wetlands for habitat or breeding are dwindling. Of particular note are the Bornean and Sumatran orang-utans. The orang-utan, the only great ape in Asia, can be found solely on the Indonesian island of Sumatra and on the Malaysian and Indonesian areas of the island of Borneo, with separate species on each island. The Bornean orang-utan (*Pongo pygmaeus)* is currently classified an endangered by The International Union for Conservation of Nature (IUCN), and the Sumatran orang-utan (*Pongo abelii*) is classified as critically endangered. Both species have decreasing population trends, attributed primarily to forest loss due to conversion of forest to agriculture and to forest fires (Ancrenaz et al., 2008). The majority of the animals are living outside of protected areas in forests that are being converted to agriculture and that are vulnerable to timber harvesting. A study by Goossens et al. (2006) in which the largest-yet genetic sample of wild orang-utan populations was used, demonstrates a recent demographic collapse of orang-utans in North Eastern Borneo. This study quantifies the effects of anthropogenic deforestation and habitat fragmentation on the apes and supports the need for major conservation efforts for the genetic viability of the species. In fact, it is predicted that the orang-utan will be completely extinct by the second decade of this century unless drastic conservation actions are taken, including establishing new conservation areas and expanding and connecting existing ones (Rijksen and Meijaard, 1999).

The orang-utan, one of four great apes in the same taxonomic group as our species (*Homo sapiens)* has been historically viewed as a human relative, and is often protected out of respect for its intrinsic value (Rijksen and Meijaard 1999). Thus, their appeal to human empathy can make them an umbrella species for conservation efforts in their habitat area. Additionally, the very health of the rainforests, which provide ecosystem services to human beings, are dependent on the orang-utan, as these apes play an essential role in seed dispersal, particularly for large seeds that are not dispersed by smaller animals (Ancrenaz et al. 2006). Orang-utans favor the lowlands, namely alluvial flood plains, peatswamp forests, and valleys (Rijksen and Meijaard 1999), with the greatest density occurring in peatswamp forests. The animals are found in greater densities in the lowlands because these areas produce more regular and larger fruit crops than dry dipterocarp forests (Ancrenaz et al. 2005). Thus, there is conservation reciprocity between the peatswamp forest and the orang-utan, with the peatswamp forests providing necessary habitat for the orang-utan, and the orang-utan providing seed-dispersing services for the peatswamp forest.

Peatland Degradation and Climate

For agricultural use, the peatlands must first be deforested, drained, and burned. Draining peat soils precludes them from being a further carbon sink, as this impedes their ability to accumulate additional organic matter, but it also releases the carbon already stored in them. As the soils are drained, the resulting aeration and decomposition of the peat leads to oxidation and, thus, CO_2 emission (Hooijer et al. 2006). In a project titled the Peat-CO2 project, emissions caused by the decomposition of drained peatlands were estimated based on data of peat depth and extent, present and projected land use and water management practice, decomposition rates, and fire emissions. Emissions were determined to be 632 Megatonnes/year (Mt/y) as of 2006. An additional 1400 Mt/y in CO2 emissions was attributed to peatland fires. This some 2000 Mt/y (over 90% of which comes from Indonesia) accounts for nearly 8% of global emissions from fossil fuel burning. Additionally, it is projected that emissions will increase if current land management practices remain the same (Hooijer et al. 2006).

Peat fires pose an additional threat to the available carbon stock in peatlands. As the soil is aerated from forest clearing or irrigation canals, the peat is much more susceptible to ignition. Peat fires typically burn aboveground and belowground not only directly affecting individual tree species, but also destroying the seedbank and the peat, which may take thousands of years to replace (Yeager, 1999). Fires are a major threat to the continued existence of the endangered orang-utan (Yeager and Fredriksson, 1999).

Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and Degradation (REDD) as Conservation Mechanisms

In light of the global implications of climate change, there is a clear need for an economically viable way for Indonesia to reduce its greenhouse gas emissions through land and water management practices, specifically through peatland forest preservation and restoration. The carbon market may provide opportunities for this to be possible.

The Kyoto Protocol, adopted by Conference of the Parties (COP) 3 in 1997, is the main mechanism guiding greenhouse gas emissions reductions worldwide. Under the Kyoto Protocol, Annex I countries, or industrialized countries, that have ratified the protocol have committed themselves to reducing their emissions by a target percentage from the 1990 baseline by 2012. Several flexible mechanisms were approved by the United Nations Framework Convention on Climate Change (UNFCCC) that allow Annex I countries to meet their emissions reductions goals, including International Emissions Trading (EIT), the Clean Development Mechanism (CDM), and Joint Implementation (JI). The CDM and JI are project-based emissions reduction mechanisms, in which Annex I countries can fund projects in non-Annex I or Annex I countries, respectively, that produce emissions reductions. Credits are given for the emissions that are avoided compared to a baseline of emissions in the absence of the project. Currently, under CDM, carbon credits can be awarded for reforestation and aforestation projects, but forest conservation and avoided deforestation are excluded. However, carbon emissions from deforestation represent 18-25% of all emissions (Stern, 2006).

As the role that intact forests play in the carbon cycle gains increasing exposure, more interest is being directed toward the possibility of a carbon trading system that credits reducing emissions from deforestation and degradation (REDD) (Murray et al. 2009). The REDD protocol would allow for forest conservation projects to qualify under the CDM. According to the Copenhagen Accord from COP 15, a REDD or REDD-plus mechanism will likely be agreed upon by the end of 2010 if a wider climate agreement can be reached (2009).

Although CDM and REDD projects do not necessarily benefit biodiversity, particularly if they target only the most cost-effective areas for reducing carbon emissions (Miles and Kapos, 2008; Venter et al., 2009a), there is a great potential for these projects to be used as a conservation mechanism. In fact, unique approaches to the issue of land conservation in this Indonesia are already being developed. For example, the Provincial government of Aceh, Fauna & Flora International, and Carbon Conservation Pty Ltd are conducting a joint project (the Ulu Masen Project) in the Aceh Province of Sumatra that uses the incentive of carbon financing to make possible community livelihood and forest protection strategies, while maintaining biodiversity values (Provincial, 2007).

This project will examine how two carbon market mechanisms, CDM and REDD, might be used in tandem to satisfy both climate mitigation and biological conservation objectives by making possible the preservation and restoration of targeted peatswamp forest areas in Indonesia.

Study Area: Block C of the Former Mega Rice Project

The Mega Rice Project in Central Kalimantan, Indonesia was initiated in 1996 with the goal of turning one million hectares of unproductive and sparsely populated lowland peat swamp forest in into rice paddies in an effort to alleviate Indonesia's growing food shortage (Boehm and Siegert, 1999). The Indonesian government made a large investment in constructing irrigation canals and removing trees, but the project did not succeed because rice could not be cultivated in the acidic soil. It was eventually abandoned after causing considerable damage to the forest (Aldhous, 2004). The former Mega Rice Project is part of a stretch of forested peatland that covers almost the entire lowland river plains of southern Borneo. Although the stretch was once connected, it is now highly fragmented, hosting only patchy populations of orang-utan, the genetic viability of which will be in question if further fragmentation continues.

The study area for this project is Block C, one of the five blocks A-E that comprise the entire Mega Rice Project (Figure 1). It is bounded by the Kahayan River to the east, the Sabangau River to the west, the Java Sea to the south, and the main Palangkaraya-Sampit road to the north. Block C and the adjacent Sabangau National Forest make up the Sabangau basin and are divided by the black water Sabangau River. The Sabangau basin is home to an estimated 7,000 orang-utans, the largest known Bornean orang-utan population in the world (Ancrenaz et al., 2008). In Block C, drainage canals were built throughout the area, but the forest was never cleared and rice never planted. Nevertheless, Block C is heavily fragmented as a result of the aeration and fires that resulted from the drainage canals, and nearly all the land is currently fallow. Additionally, Block C is currently designated for agriculture, although no effort has been made for agricultural development in the area since the failed Mega Rice Project. All of the fragmented forest blocks in Block C are reported to contain orang-utans.

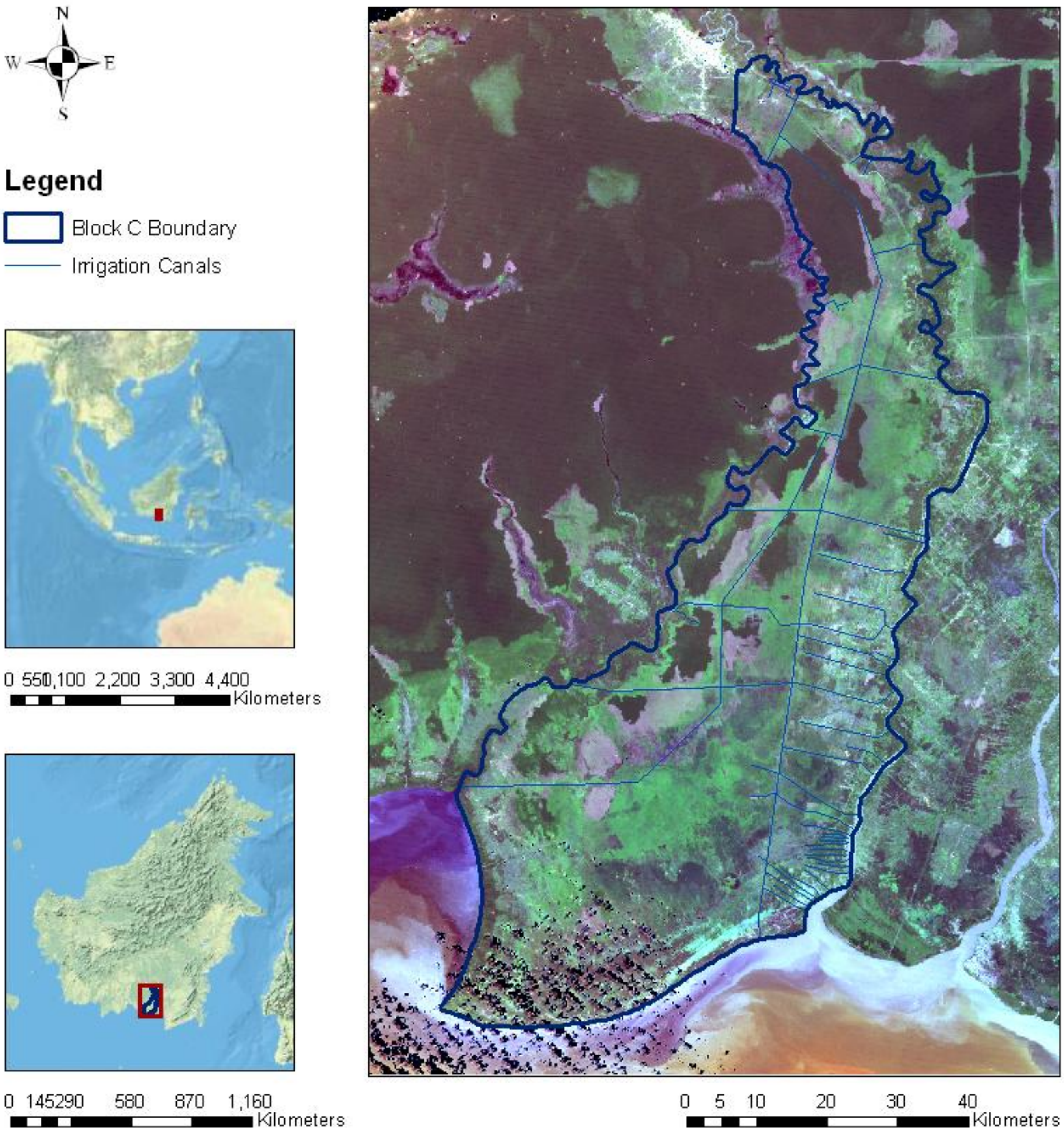

Figure 1. Study Area: Block C of the former Mega Rice Project in Central Kalimantan, Indonesia (Borneo).

Objectives

In order to increase habitat connectivity necessary for the survival of orang-utans in Block C, orang-utan subpopulation locations need to be identified, and broad corridors between existing subpopulations should be established through degraded areas. Additionally, financial incentive needs to be provided for this land conservation and restoration to be economically viable. This study takes into account not only the suitability of the land as orang-utan habitat, but also its potential for carbon sequestration and, thus, potential value on the carbon market. This spatially-explicit, landscape-scale analysis of Block C explores how the conservation objectives of ape preservation and carbon sequestration and storage can be mutually satisfied through land management strategies.

Specifically, the objectives of this study were to prioritize intact forest patches for conservation based on orang-utan presence and potential to support orang-utan subpopulations and to identify corridors through degraded areas that take into consideration the value of the land both in terms of potential to enhance orang-utan population viability and to sequester carbon.

Methods

In order to construct a land management strategy that benefits orang-utan viability and carbon storage potential on Block C, I prioritized intact forest patches for conservation and identified corridors through degraded areas that would connect priority patches. I first identified intact habitat patches from satellite imagery and then prioritized these patches for conservation based on their patch geometry metrics and on orang-utan presence as determined by direct field surveys. Then, I created a species distribution model (SDM) and prioritized areas for restoration based on habitat suitability as indicated by the SDM and on potential carbon value.

2.1 Patch Prioritization

Land Use / Land Cover Classification, Orang-utan Habitat Patch Identification, and Patch Geometry

The following data was provided by Simon Husson of the University of Cambridge and the Orang-utan Tropical Peatland Project (OuTrop) in L1G format: Landsat 7 TM Imagery, acquisition date 5 August 2007, UTM Zone 49S, WGS 1984. L1G products are geometrically corrected, and geometric accuracy should be within 250 meters for low-relief areas at sea level, such as the study site.

I conducted radiometric and atmospheric correction in ERDAS Imagine 9.3 (Appendix A), and then masked the image to represent Block C of the Mega Rice project with a shapefile provided by Agata Hoscilo of Leichester University. I excluded the thermal band, band 6, from the analysis and created a layerstack of bands 1, 2, 3, 4, 5, and 7. In order to mask out the clouds from the image, I created tasseled cap index from the layerstack, because the clouds were easily distinguishable from other land cover classes in the tasseled cap index. In a remotely sensed dataset, the samples can be plotted in multi-dimensional space along axes composed of the spectral bands. Each sample point, then, can be defined as its coordinate point on each of the axes. For a more informative and clear interpretation of the samples, the axes can be realigned so that they emphasize the structure in the data (Crist and Kauth, 1986). In this way, the Tasseled Cap Index describes that data in terms of brightness, greenness, and wetness along axis 1, 2 and 3, respectively. I ran an Iterative Self-Organizing Data Analysis Technique (ISODATA) unsupervised classification of the tasseled cap image in Erdas IMAGINE, and identified classes that appeared to represent clouds, cloud shadow, and error, and masked these areas out of the image.

I computed a Principle Components Analysis (PCA) and a Normalized Difference Vegetation Index (NDVI). PCA is similar to the Tasseled Cap Index in that it is a method of realigning the data along different axes in order to better describe it. In PCA, the matrix of samples is multiplied by a transformation matrix, and the data is essentially reprojected along new axes. The aim of PCA is to find this transformation matrix by analyzing a secondary matrix derived from the primary matrix. To do this, the dataset is basically regressed on itself. The first principal component is fitted by least-squares, and it captures maximum sample variability in the dataset along its axis. Each subsequent component drawn orthogonal to the first principal component and is fitted to the residuals. In doing this, PCA reduces a dataset of p variables to a smaller number of fabricated variables that more succinctly capture most of the information present in the dataset (McCune and Grace, 2002).

NDVI is a commonly used vegetation index that can be calculated as:

(Near Infrared - Red) / (Near infrared + Red).

The premise is that vegetation reflects the near infrared portion of the electromagnetic spectrum and absorbs the red portion. Thus, this index is successful at differentiating vegetation from background soil. The output is normalized from -1 to 1, with 1 representing areas that are highly vegetated.

I determined which bands should be used in the final, supervised classification by exploring which combinations of bands would best enable me to distinguish between land cover classes. To do this, I created layerstacks of various combinations of bands from the original Landsat TM 7 bands, PCA, NDVI, and tasseled cap index, and ran unsupervised classifications of those layerstacks. The most successful layerstack included Landsat TM 7 Bands 2- 5 and PCA Bands 1 and 2, and so this was used for the supervised classification. Training sites for spectral signatures were selected from this image based on on-the-ground knowledge of the study area. Distinct training sites were created for the following LULC categories: barren or recently burned, grassland or shrubland, water or inundated, PSF, and degraded or secondary PSF. I evaluated the signatures by viewing the band-by-band histograms of the selected signatures, by plotting the signatures in feature space in separate viewers using Landsat TM Band 4 (near infrared) and Landsat TM Band 3 (red), and by viewing a contingency matrix, which displayed how many pixels in each training sample were assigned to each class.

Once I finalized the signatures, a supervised classification was then run using the Minimum Distance decision rule.

This classified image was imported into ArcGIS v.9.3 (ESRI, 2008), and irrigation canals were incorporated into the image based on locations provided by Agata Hoscilo. Agricultural areas were often confused with other LULC classes because the agricultural plots were comprised of a combination of dry soil, sparsely vegetated areas, and crops. However, agricultural areas were easy to distinguish with the naked eye due to visible fine-scale irrigation canals running throughout, and so I hand-digitized the agricultural areas in Block C.

In order to identify patches of suitable orang-utan habitat, I masked out unsuitable LULC types and retained just the PSF and degraded / secondary PSF land cover types. I then bundled the clusters of pixels designated as habitat into distinct patches. Then, I selected a minimum patch size of 350 hectares, considered the minimum patch size required to support one female orang-utan (Galdikas, 1988). All patches smaller than 350 hectares were masked out. Mangrove areas were easily confused with PSF areas, and so habitat patches consisting of mangrove swamp were masked out and excluded from the analysis.

I computed patch geometry metrics on the habitat patches in order to prioritize them for conservation. Patch geometry metrics have their roots in island biogeography theory, and are one method of identifying which patches might be most suitable to support species. I computed area, thickness, core-area ratio, and shape index for each patch. Thickness is the maximum patch width, and shape Index was calculated using the following formula:

*Shape Index = Patch Perimeter / (4 * sqrt(PatchArea)).*

For core-area ratio, core was defined as peatland area at least 200m from any non-habitat. In this case, degraded and secondary PSF areas were considered non-habitat so that the area defined as core only included intact PSF with a buffer of intact PSF.

I then reclassified the values for each of the metrics patch area, core-area ratio, patch thickness and shape index to a common scale and summed the values of all of the metrics for each patch. I highlighted the importance of patch area by giving it a 67% influence. The other three metrics received an 11% influence. I specified this distribution of influence for each patch metric because, although patch area is important to consider when estimating the habitat suitability of a patch, it is essential to consider the quality of the patch as well. For example, if a patch is large but "sprawling," it may not be as valuable as a large, condensed patch.

Orang-utan Presence

Field surveys were conducted in June and July 2009 through the Orang-utan Tropical Peatland Research Project (OuTrop), a project of the Center for International Cooperation in the Sustainable Management of Tropical Peatland (CIMTROP) of the University of Palangkaraya, Central Kalimantan, Indonesia. Line transects were hand-cut through six forested patches on Block C (Figure 2). In the northernmost survey area, eight transects were cut perpendicular to an irrigation canal that intersects the study area into two forest fragments. Three transects were cut on the eastern patch at 50 degrees, and five were cut on the western patch at 230 degrees. The northernmost transect on the western side of the canal was a previously-existing research transect. In the central study area, nine transects were surveyed. These transects were cut perpendicular to the Sabangau River going due east. In the southern part of the study area, eleven transects were cut in four forest blocks. Because the forest patches were narrower than 1km in width in some places, the transects were cut at various angles to minimize the likelihood of reaching the forest edge before completing the entire transect. Imagery from Google Earth was used as a reference.

Each transect was intended to be 1km in length and cut in a single direction. However, some of the transects reached the forest edge before they were 1km in length. In these cases, the transect was continued at a different angle whenever possible and was truncated whenever continuing in a different angle was not possible. A total of 28 transects were completed, totaling 26.32 kilometers surveyed. Each transect was marked at 25m intervals using a measuring tape. Observers walked slowly along the transects, looking in all directions for orang-utan sleeping nests as a proxy for orang-utan sightings. For each nest sighting, the distance along the transect was estimated, the perpendicular distance from the transect was measured, the nest height was estimated at 5m increments, and the nest size was estimated at .5m increments. The nest decay stage was also classified as one of the following categories: A: New, leaves still green, B: Older, nest still in original shape, with brown leaves attached, C: Old, holes in the nest, or D: Very old, nest no longer in original shape, but some twigs and branches still present. Survey data is available upon request.

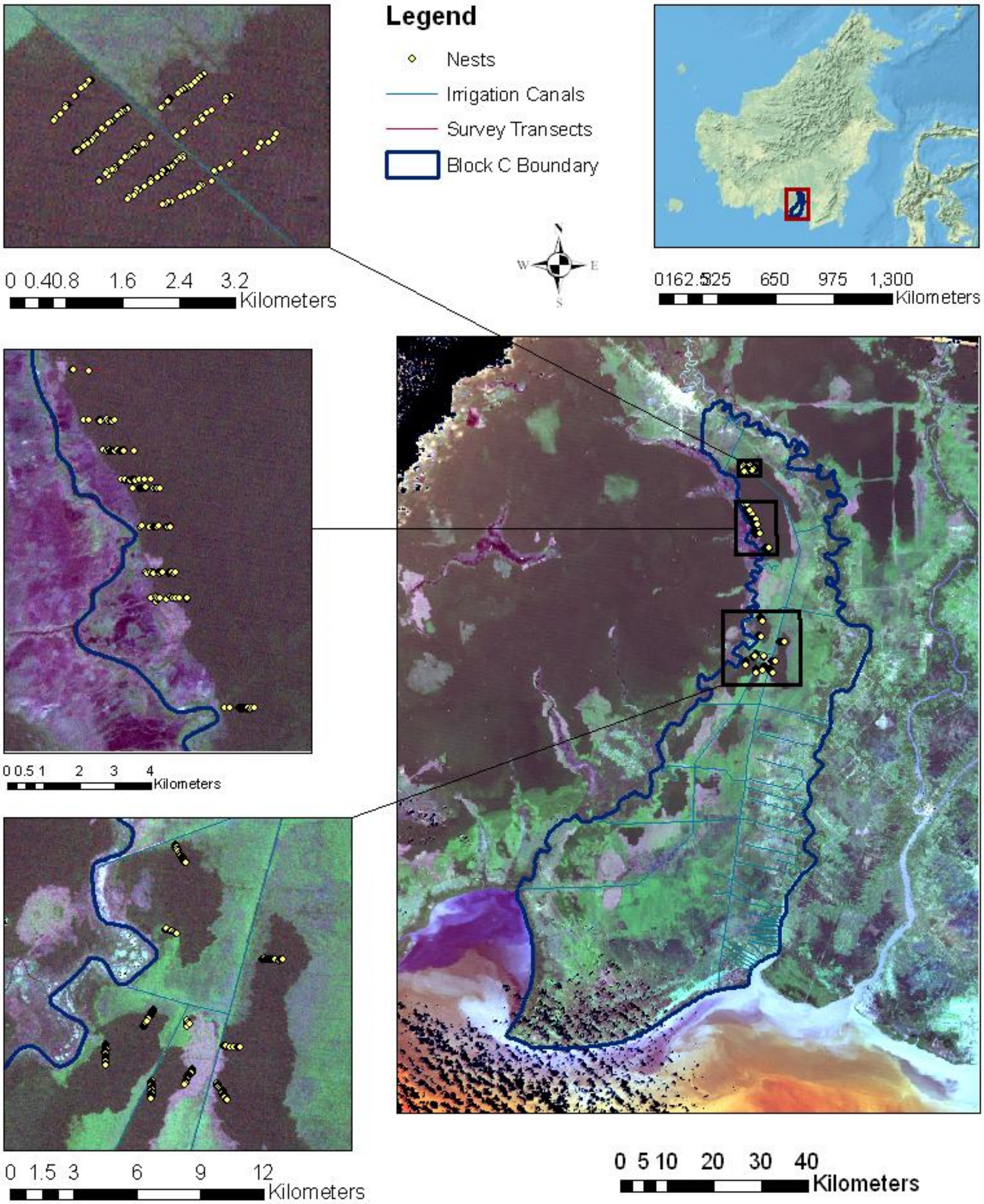

Figure 2. Survey transects and nest sighting locations in Block C of the former Mega Rice Project.

The software program DISTANCE 3.5 (Thomas et al., 1998) was used to produce an orang-utan nest density estimate for the blocks that were surveyed. This program uses the distance sampling methods described by Buckland et al. (1993). In this case, the data entered included total transect length of each transect (in kilometers), the number of nests observed, the patch in which the transect was cut, perpendicular distance from the transect for each nest observed (in meters), and patch size (in kilometers, as determined by the LULC classification). The software fits several possible robust, semi-parametric models to the data to determine the probability of detection as a function of the distance of the observed nest from the transect, thus estimating an effective strip width (ESW). So, the detection function describes the probability of detecting a nest given it is *x* distance away from the transect. ESW was estimated regionally (Block C).

I first truncated the data at 30m based on the boxplots, and ran this truncated dataset using the following key function/series expansion combinations: Half-normal + cosine, uniform + cosine, hazard-rate + simple polynomial, half-normal + hermite polynomial, uniform + simple polynomial, and hazard-rate + cosine. The models were evaluated based on the lowest AIC, and the Half-normal + cosine model was selected (AIC = 4038.73). This was divided into ten intervals to smooth the histogram. The resulting model produced an AIC of 2620.34 and the probability of a greater Chi-square goodness of fit value, P = 0.19053. The model estimated the effective strip width at 13.09m.

Nest density was estimated locally (per patch) using the following formula (S. Husson, pers. comm.):

$$Nest\ density = N / L \times 2w,$$

where N is the number of observed nests per patch, taking into account the truncation; L is the sum of the lengths of the transects in km per patch; and w is the effective strip width in km. Because transects were completed in only 6 of the 24 patches, the regional nest density estimate, 944.765 nests / km^2, was used for the 18 patches without direct measurements.

To estimate population densities of orang-utans based nest observations, I used the following formula (Morrogh-Bernard et al., 2003):

$$D = N / (p * r * t),$$

in which D is orang-utan density (animals/km^2), N is nest density, p is the proportion of nest builders in the population, r is the rate at which nests are produced (n/day/individual), and t is the decay rate of nests, or time during which a nest remains viable (days).

Accuracy of the values used for the parameters p, r, and t are vital for producing accurate orang-utan density estimates. However, these values can vary considerably between field sites, and measuring them directly would require intensive field survey (Morrogh-Bernard et al., 2003). Therefore, I used values designated in Husson et al. (2008) for the adjacent catchment, the Sabangau catchment, to estimate the parameters. The climatic and ape behavioral variables are similar between the

Sabangau catchment and Block C, and so estimations of *p*, *r*, and *t* for the Sabangau catchment are appropriate for Block C as well. The authors found that the proportion of nest builders in the population (*p*) is similar for sites across Borneo and Sumatra, and estimated this number at 0.89 for Sabangau. The rate at which nests are produced (*r*), 1.17, was derived from studies of direct observation in Sabangau. The decay rate of the nests (*t*), or time for which the nest remains visible is highly variable between sites across Borneo and Sumatra, and an accurate model for *t* is yet to be developed. This parameter is likely to be heavily dependent on climatic factors (humidity, temperature, rainfall), building time and complexity (day nest versus night nest), and wood density of the parent tree. *t* was estimated at 365 days for Sabangau based on studies documenting the observed time in days from construction to complete degradation for a group of nests.

I estimated orang-utan numbers for each forest patch based on estimated orang-utan density and patch size. For patches that were not directly surveyed, the regional density was used.

2.2 Corridor Identification

The datasets described below were prepared by the World Resources Institute for use in the Interactive Atlas of Indonesia's Forests (Minnemeyer et al., 2009):

- Rivers: This data displays the rivers of South East Asia, originally produced by Bakosurtanal, the Indonesian National Coordinating Agency for Surveys and Mapping.

- Roads: This dataset displays detailed roads for Indonesia. It comes from the basemaps of Indonesia, developed by Bakosurtanal. The time period corresponds to the 2003 situation of roads including logging roads.
- Fire Locations, 2003-2007: This data displays fire occurrences (active fires detected) in 2003, 2004, 2005, 2006, and 2007 in Indonesia and was produced by the University of Maryland (UMD) Fire Information for Resource Management System. The data are active fire locations detected by the MODIS sensor on board the Terra and Aqua satellites.
- Peat Depth: This data displays the peat lands of Indonesia. It was digitized by Sekala (a local non-profit organization), from 3 atlases of peat land distribution in Sumatra, Kalimantan, and Papua (Wetlands International - Indonesia Program & Wildlife Habitat Canada, 2003, 2004, and 2001).
- Carbon: This data displays the carbon stock of above/below ground biomass (Tier-1 IPCC GPG-LULUCF) generated from the Joint Research Centre's GLC2000 Landcover dataset. Pixel value = Carbon density (TC/Ha).

Species Distribution Model

The maximum entropy method (maxent) of predictive modeling was used to create the orang-utan distribution model. Maxent is a method of estimating the probability distribution of observed samples. The model sets the constraint that the mean of the distribution for each variable must match the mean of the observed data. Thus, the model fits the available data distribution as loosely as possible, or the distribution can approach disorder (maximum entropy) (Phillips et al., 2006). It aims to describe the data accurately while assuming nothing about what is unknown (Jaynes, 1990). In the context of modeling for species geographic distributions, the model considers the characteristics of a site in which a species was observed, but does not assume anything about the sites in which the species was not observed. Thus, maxent is a generative modeling approach which aims to describe "habitat," as opposed to a discriminative approach which aims to separate "habitat" from "non-habitat." Because the model uses presence-only data to predict habitat, this approach is particularly useful in this circumstances such as this in which absence data are not available (Elith et al., 2006).

I used the *Maxent* 3.3.2 software program (Phillips et al., 2006) to predict the habitat preferences of the Bornean orang-utan. This software uses a maximum entropy method of modeling. The presence-only data was entered into *maxent* along with the environmental variables to fit the model. The output included graphic displays of the response curve of each environmental variable, a graphic display of the jack-knife test of variable importance, estimates of the explanatory power of each variable, suggested cut-off values for model tuning, and a tuning tool that is similar to a ROC curve. The jack-knifing procedure run by *maxent* estimates the explanatory power that each variable contributes when considered in isolation and the explanatory power when all variables except for one are considered.

Maxent was used for model tuning. Because *maxent* uses presence-only data, the ROC curve produced by *maxent* can accurately represent true positives, but it must estimate negatives. It does this by calculating the proportion of the background cases that are predicted to be habitat. Thus, tuning with the *maxent*-derived ROC involves maximizing the presence samples predicted to be habitat while minimizing the total area predicted to be habitat.

The following metrics were gathered or computed and entered into the maxent model:

1. Euclidean distance to nearest river. Distance to rivers is a proxy for forest productivity, as it is higher at the river's edge, with additional nutrient and light inputs. (Figure 12 in Appendix B)
2. Euclidean distance to nearest canal (Figure 12 in Appendix B)
3. Euclidean distance to nearest road (Figure 12 in Appendix B)
4. Euclidean distance to Agriculture (Figure 12 in Appendix B)
5. Euclidean distance from the nearest 2003 fire (Figure 13 in Appendix B)
6. Euclidean distance from the nearest 2004 fire (Figure 13 in Appendix B)
7. Euclidean distance from the nearest 2005 fire (Figure 13 in Appendix B)
8. Euclidean distance from the nearest 2006 fire (Figure 13 in Appendix B)
9. Euclidean distance from the nearest 2007 fire (Figure 13 in Appendix B)
10. LULC (Figure 3)
11. CA_Ha_ton (soil carbon) (Figure 12 in Appendix B)
12. Peat depth (thickness in cm) (Figure 12 in Appendix B)

Because LULC had a dominating effect on the model, it was removed for the second run, and the following variables were added (Figure 4):

1. Patch Area
2. Patch Shape Index
3. Patch Core-Area Ratio
4. Patch Thickness

Corridors

I used a least-cost corridor method of identifying the ideal connection locations between the priority patches. In this method, the output from the species distribution model was used as the cost surface, which indicates how taxing the landscape is to traverse for an orang-utan (Figure 3). To specify, areas that the SDM designated as low quality habitat are considered taxing and high quality habitat areas are not. I calculated the accumulative cost of traveling away from a designated patch as a function of the distance from that patch for each of the priority patches. To find the lowest-cost corridor from one patch to another, these accumulative cost layers were added together for each patch pair and thresholded at 15%.

I then identified corridors between priority habitat patches that consider not only habitat suitability, but also the carbon value of the land. The output of the SDM and the carbon dataset described above were reweighted to a common scale and added together to create the cost surface (Figure 3). In this case, areas of high carbon value and high habitat suitability were considered low-cost, and areas of low carbon value and low habitat suitability were considered high-cost. The corridor analysis was repeated, again identifying the lowest-cost corridors between priority patches. GIS models are available upon request.

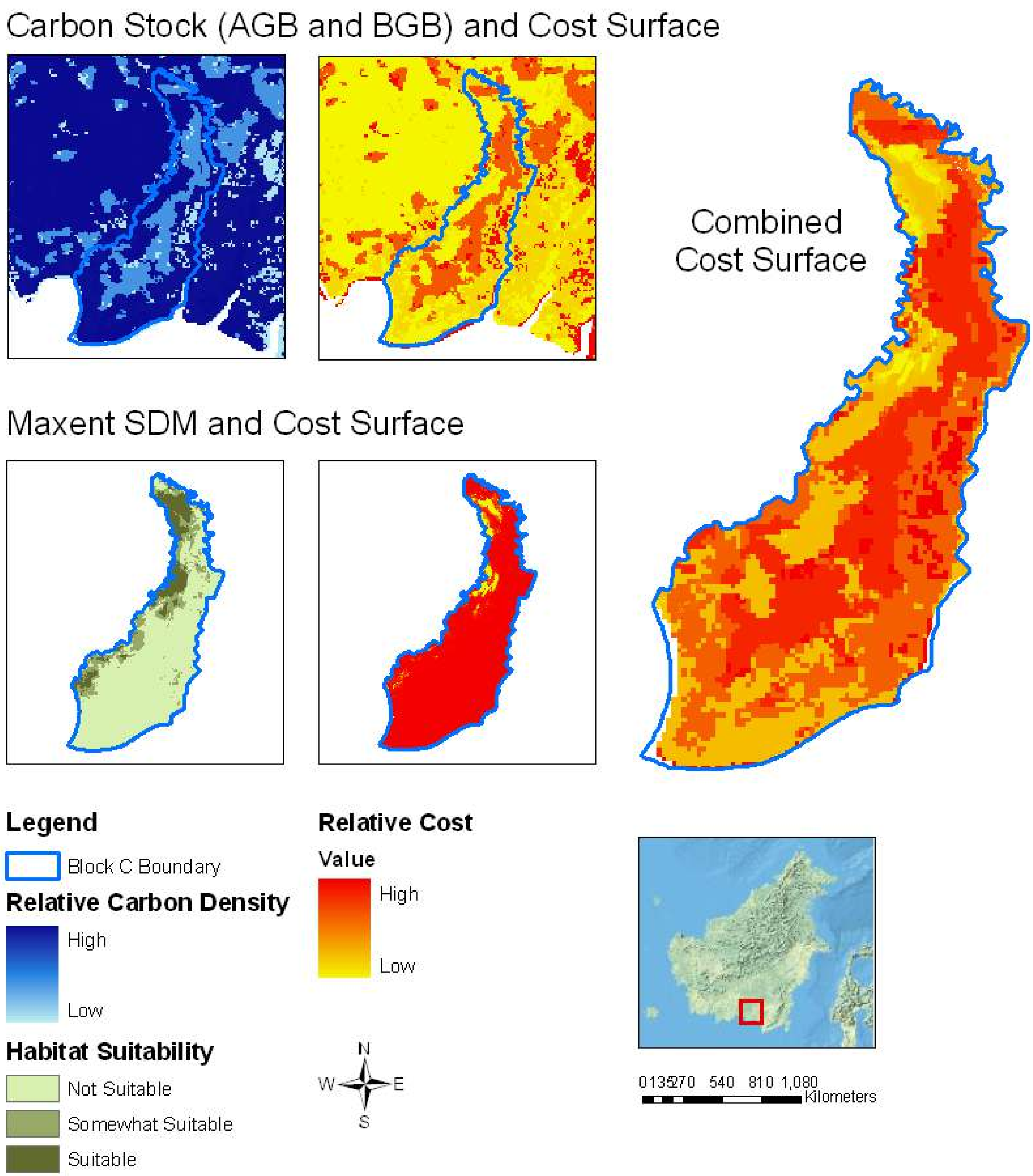

Figure 3. Cost Surfaces for corridor paths consisting of the maxent species distribution model, aboveground and belowground carbon stock, and a combined surface.

Results

3.1 Patch Prioritization

Land Use / Land Cover Classification, Orang-utan Habitat Patch Identification, and Patch Geometry

The LULC classification indicated that about 40% of the area in Block C is shrubland / grassland land cover type (Figure 4 and Table 1). Intact PSF makes up only about 20% of the area, and this area increases to 30% if degraded or secondary PSF is included. Most of the area devoted to agriculture appears to be along the eastern side of Block C, and this area is also largely devoid of habitat patches. The barren and burned areas appear to be somewhat concentrated along the irrigation canals. I identified 24 habitat patches larger than 350 hectares in Block C.

Table 1: Land cover type occurrence in hectares and percent cover in Block C of the Mega Rice catchment with agriculture hand-digitized

Landcover Type	Area (hectares)	% Cover
Shrubland / Grassland	186,345	41.51
Peatswamp Forest	87,315	19.45
Barren / Burned	55,743	12.42
Degraded or secondary peatswamp forest	38,074	8.48
Water / Inundated	19,401	4.32
Agriculture	59,802	13.32
Canals	2,240	0.50

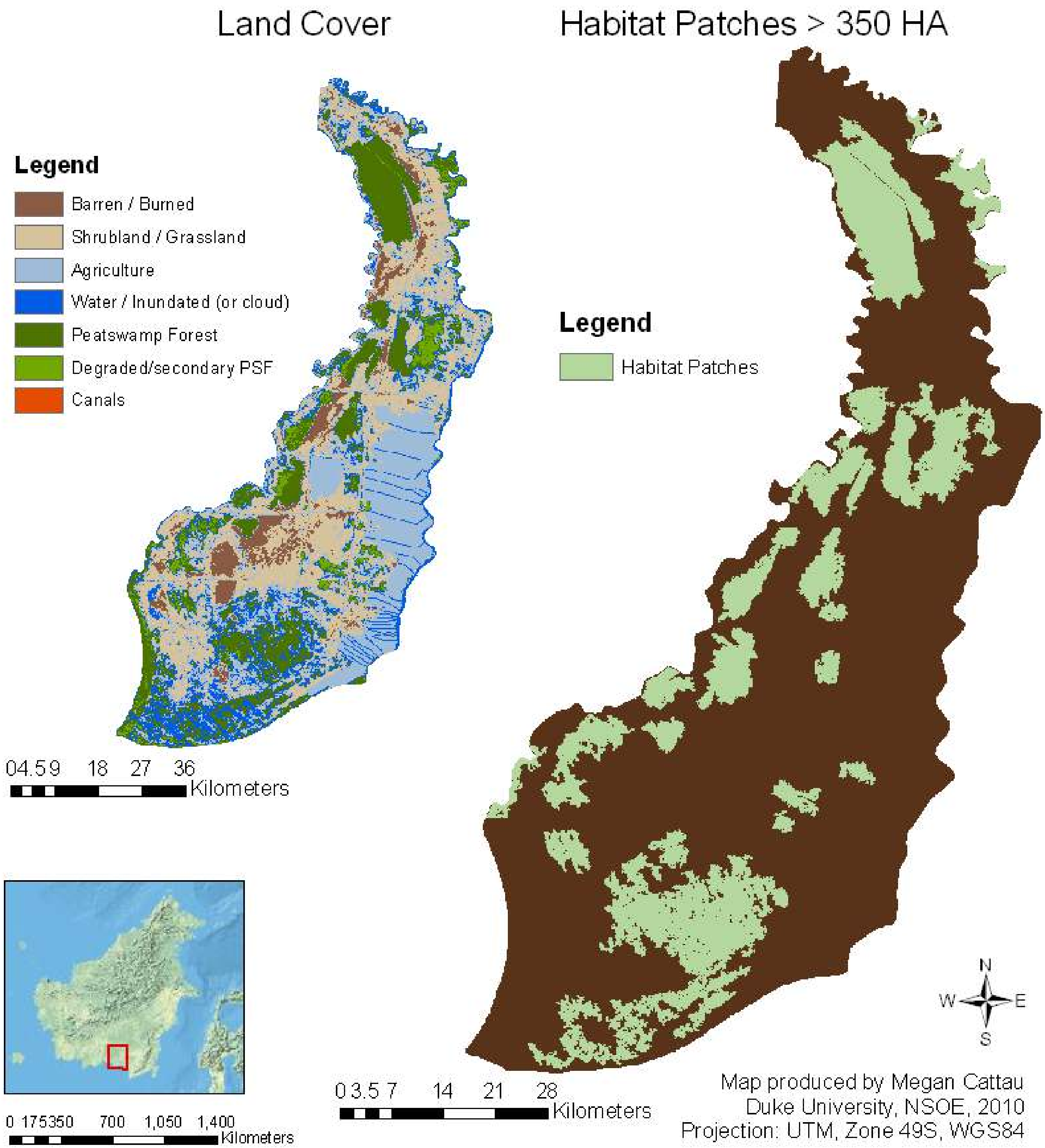

Figure 4. Land cover classes and orang-utan habitat patches in Block C of the Mega-Rice Project

The area of the patches ranges from 408 hectares to 22,653 hectares, the thickness from 105 to 3,485 meters, the core-area ratio from 0 to 84, and the shape index from 3.2 to 79.6 (Table 2 and Figure 5). The five patches with the highest conservation priority include patch 2, 3, 6, 13, and 24 (Figures 6 and 8). The patch with the highest relative conservation value is Patch 3. Patch 3 is the second-largest patch, has the highest core-area ratio and thickness and a relatively low shape index. Patch 2, which is adjacent to Patch 3, is not one of the largest patches, but it has one of the largest thickness measurements and the second-highest core-area ratio. Although this was not considered in the prioritization, its close proximity to Patch 3 also makes it an attractive candidate to reconnect to other patches, as it could be relatively easy to do. Patch 6 is relatively large and thick, and Patch 13 is somewhat large and thick with a low shape index. Patch 24, which is located in the southernmost part of Block C, is the largest patch. However, it also has the highest shape index, indicating that this patch is not condensed. Therefore, although this patch is quite valuable due to its large area, its relative conservation value is decreased somewhat by its shape.

Table 2: Patch metrics of orang-utan habitat patches in Block C of the Mega Rice catchment

Patch	Area (hectares)	Thickness (meters)	Core-Area Ratio	Shape Index	Relative Conservation Priority
1	456	153.63	0.00	12.04	22
2	4433	1663.17	0.55	7.24	2
3	13851	3485.13	0.84	3.62	1
4	2842	495.00	0.00	13.88	12
5	420	453.63	0.00	4.49	18
6	9669	1666.05	0.25	31.47	4
7	2075	1641.39	0.45	6.41	6
8	3548	1274.13	0.23	13.12	8
9	912	762.99	0.43	3.28	14
10	3088	676.05	0.00	19.97	10
11	3053	1376.55	0.45	8.16	7
12	408	285.00	0.00	17.61	22
13	4440	1404.45	0.09	8.46	3
14	653	141.21	0.00	25.02	24
15	1700	538.47	0.02	11.85	13
16	3852	729.93	0.00	33.73	9
17	1324	1454.13	0.43	3.17	10
18	991	408.15	0.00	16.77	17
19	640	358.47	0.00	9.03	21
20	1086	405.00	0.00	13.74	16
21	412	460.89	0.00	5.90	18
22	1552	475.41	0.00	17.26	15
23	752	105.00	0.00	32.95	20
24	22653	628.47	0.04	79.61	4

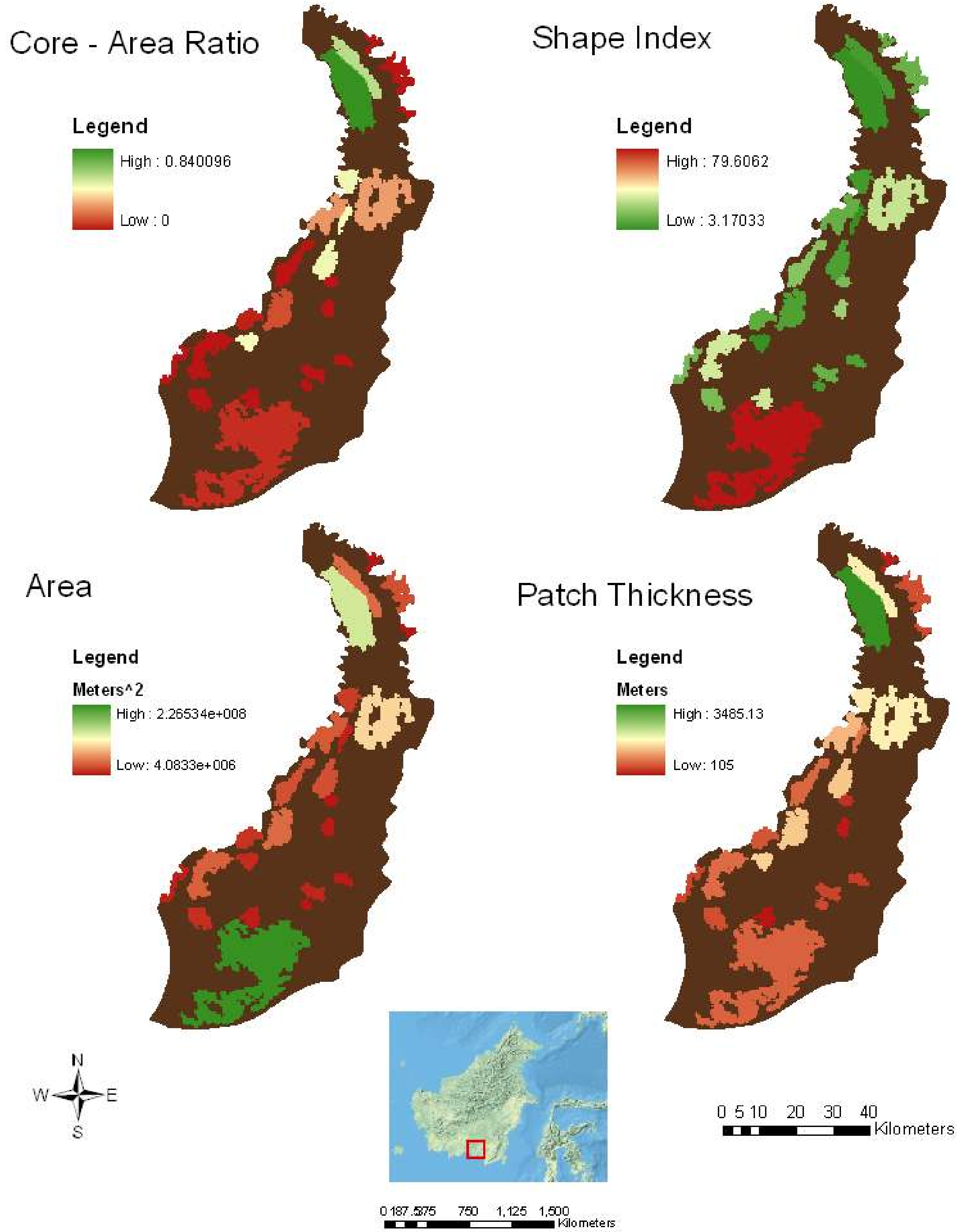

Figure 5. Patch Geometry Metrics computed for the orang-utan habitat patches: area, patch thickness, shape index, and core-area ratio.

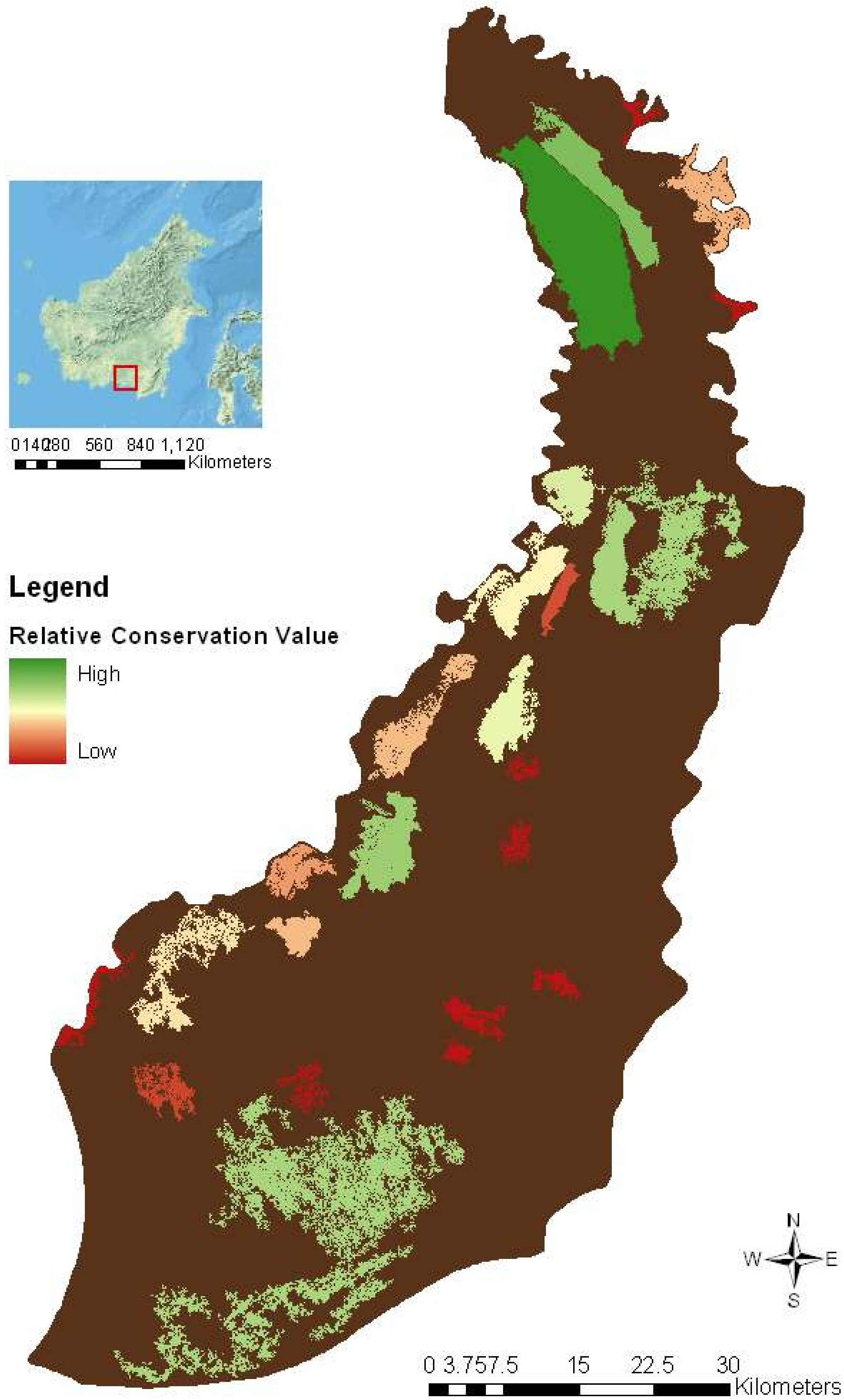

Figure 6. Patch prioritization of orang-utan habitat patches based solely on patch geometry metrics.

Orang-utan Presence

The *DISTANCE* analysis indicated that the survey had an effective strip width of 13.09 meters, and that the nest density estimate for the surveyed area is 944.765 nests / km^2 (analytic coefficient of variance: 0.109). The regional density estimate of orang-utans in the survey area is 2.517 individuals / km^2. This is relatively dense, compared to the density estimate of the adjacent Sabangau area of 1.93 individuals / km^2 (Husson et al., 2008). The population size over the entire Block C is 2,161 individuals (Table 3 and Figure 7). However, the proposed minimum viable population size is 250 individuals (Singleton et al., 2004), and only three of these forest patches supports 250 individuals or greater when considered in isolation: Patch 3 with 271 individuals, Patch 6 with 311, and highly-patchy Patch 24 with 563 (in bold in Table 3). Therefore, if the habitat patches are entirely isolated, then the viable population size of the entire Block C is reduced to 1,146 individuals. This fact highlights the importance of orang-utan habitat connectivity in Block C.

The five patches that contain the greatest estimated number of individuals include patches 3, 6, 8, 13, and 24. The five patches with the highest value based on the patch geometry metrics include patch 2, 3, 6, 13 and 24. Thus, the final six priority patches for conservation include patches 2, 3, 6, 8, 13, and 24 (Figure 8). It is recommended that these patches be connected to increase orang-utan viability.

Table 3: Nest density, orang-utan density, and number of orang-utan individuals in each patch in Block C of the Mega Rice catchment

Patch	Nest Density (nests / km^2)	OU Density (individuals / km^2)	Orang-utan Individuals	Relative Conservation Priority
1	944.765	2.486	*11*	21
2	611.154	1.608	71	9
3	**744.911**	**1.960**	**271**	3
4	944.765	2.486	*71*	9
5	944.765	2.486	*10*	22
6	**1222.307**	**3.216**	**311**	2
7	1098.167	2.889	60	11
8	1757.006	4.623	164	4
9	1359.073	3.576	33	14
10	944.765	2.486	*77*	7
11	944.765	2.486	*76*	8
12	944.765	2.486	*10*	22
13	944.765	2.486	*110*	5
14	944.765	2.486	*16*	19
15	944.765	2.486	*42*	12
16	944.765	2.486	*96*	6
17	944.765	2.486	*33*	14
18	944.765	2.486	*25*	17
19	944.765	2.486	*16*	19
20	944.765	2.486	*27*	16
21	944.765	2.486	*10*	22
22	944.765	2.486	*39*	13
23	944.765	2.486	*19*	18
24	**944.765**	**2.486**	***563***	1
Total			**2,161**	

* Estimates of orang-utan individuals based on the regional nest density estimate are shown in *italics*

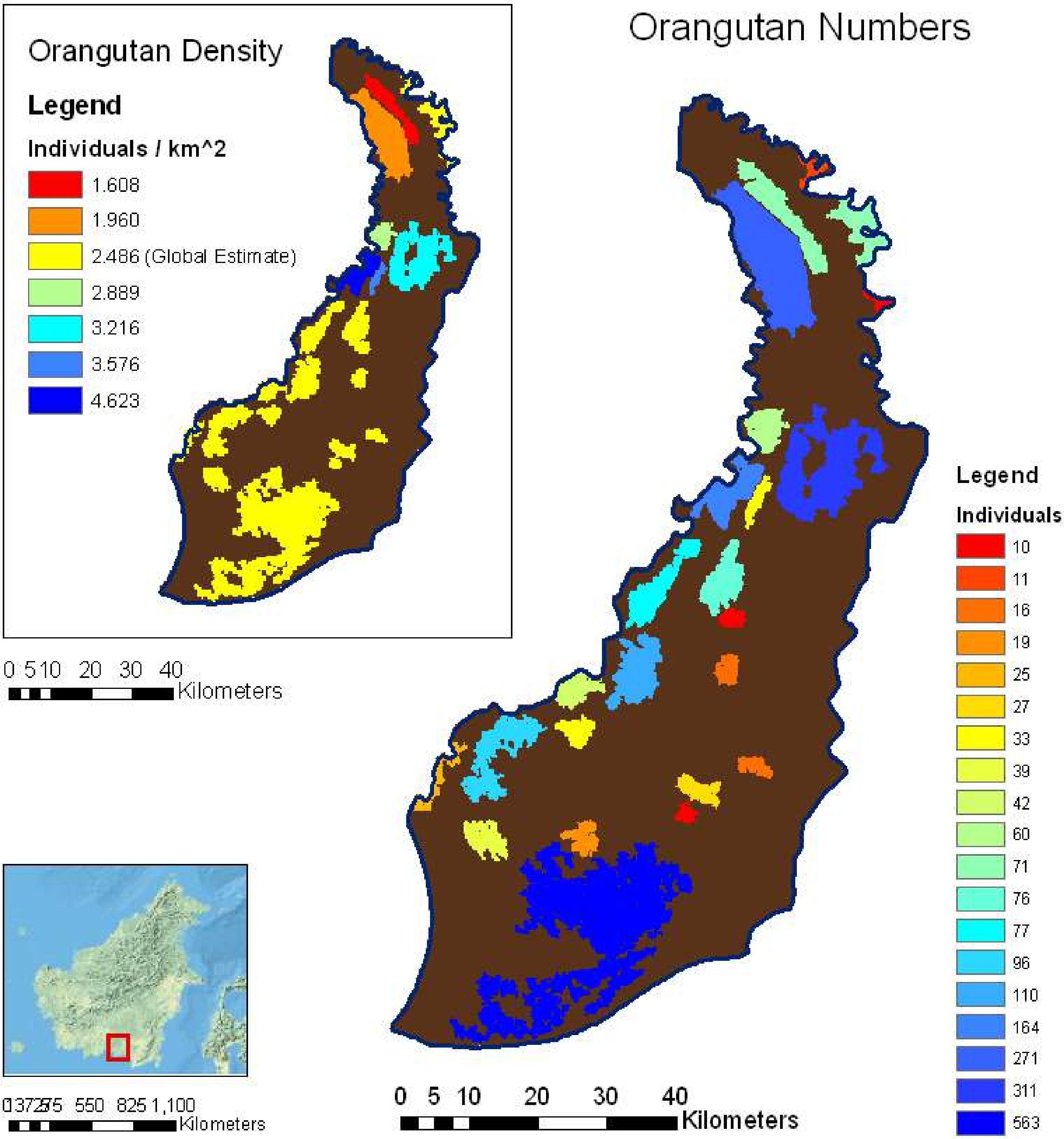

Figure 7. Orang-utan density and number of orang-utan individuals by patch.

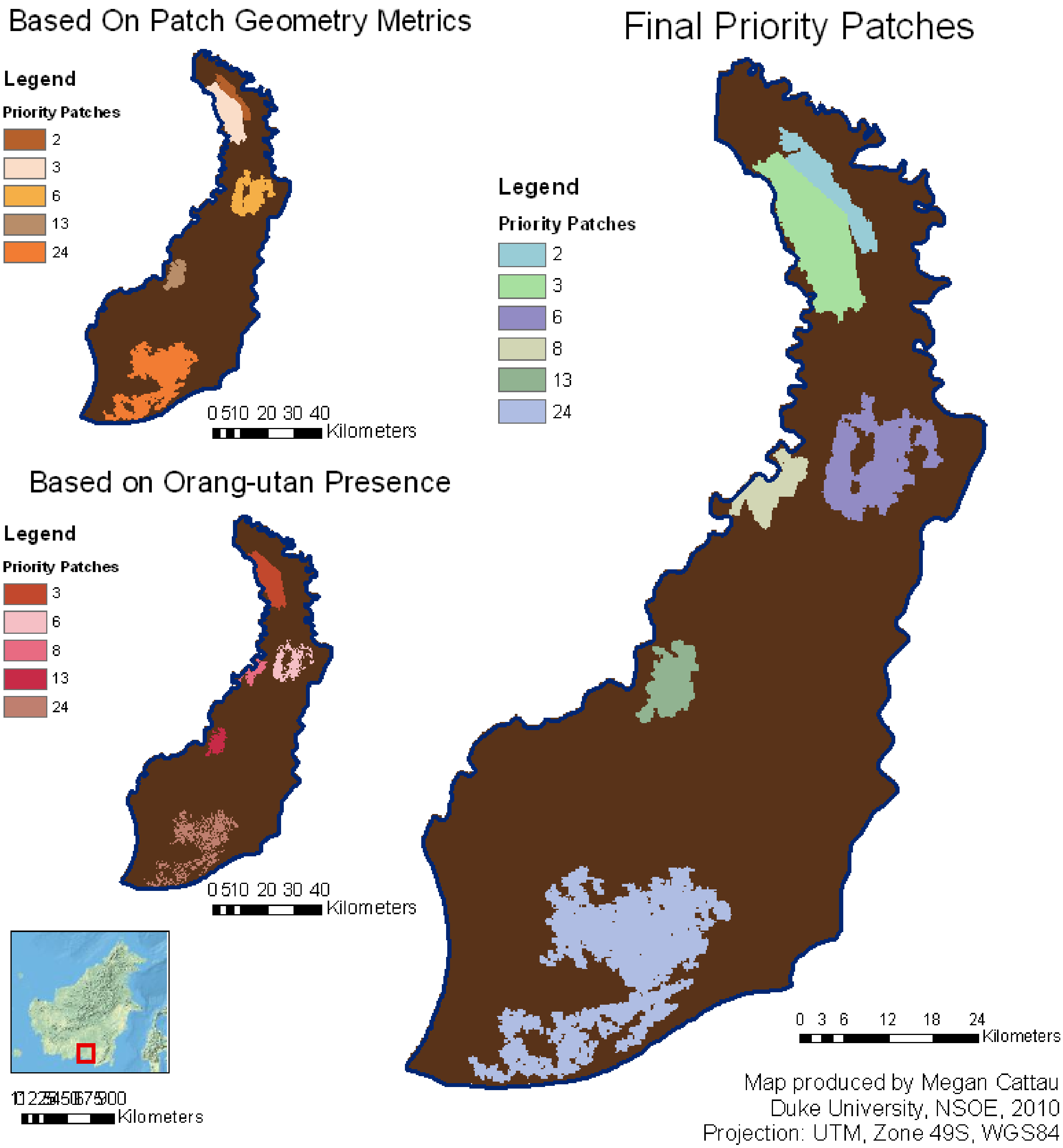

Figure 8. Priority patches based on patch geometry metrics and orang-utan presence.

3.2 Corridor Identification

Species Distribution Model

The variables that contribute most to the species distribution model (10% contribution or more) include (Table 4): LULC, Distance to 2007 fires, and Distance to Rivers. The jack-knifing procedure run by *Maxent* shows that Distance to 2007 fire contributes the most gain when considered in isolation, so it has the most information by itself. The variable that decreases the gain most when omitted is LULC, so it has the most information that is not present in other variables.

Table 4: Relative explanatory power of each predictor variable with greater than 1% contribution as determined by *Maxent*

Variable	Percent contribution
Land use / land cover	35.3
Distance to 2007 Fire	26.8
Distance to Rivers	23.1
Distance to Canals	4.7
Distance to 2004 Fire	4.2
Distance to Agriculture	3.3

Because the variable LULC dominates the model with 35% contribution, and because it is well-understood that land cover is the predominant factor in orang-utan nesting site choice (they will not nest in non-forested areas), the variable was removed from the model. The second run, without LULC and with the patch metrics included indicates that the variables that contribute most to the model (10% contribution or more) include: Distance to 2007 fires, Patch Core-Area Ratio, Distance to Rivers, and Distance to canals (Table 5). These variables were present in this order of percent contribution in the previous run as well, with the exception of Patch Core-Area Ratio, which was not included. The jack-knifing procedure run by *Maxent* (Figure 9) shows that Distance to 2007 fire contributes the most gain when considered in isolation, so it has the most information by itself. Other variables that contribute a relative large amount of information when considered in isolations include (more than 0.7 Gain): Distance to canals, Distance to Rivers, and Patch Core-Area Ratio. The variable that decreases the gain most when omitted is Distance to river, so it has the most information that is not present in other variables. Other variables that contribute a relative large amount of information not contributed by other variables include: Distance to 2004 fires, and Distance to 2006 fires. Model outputs for both runs are displayed in Figure 10.

Table 5: Relative explanatory power of each predictor variable with greater than 1% contribution as determined by *Maxent*

Variable	Percent contribution
Distance to 2007 Fire	24.6
Patch Core-area Ratio	21.9
Distance to Rivers	12.1
Distance to Canals	12.1
Distance to 2004 Fire	5.7
Distance to Agriculture	5.6
Distance to 2006 Fire	4.6
Ca_Ha_ton	3.5
Peat Depth	3.2
Distance to 2003 Fire	2.5
Patch Shape Index	1.6
Patch Thickness	1.2

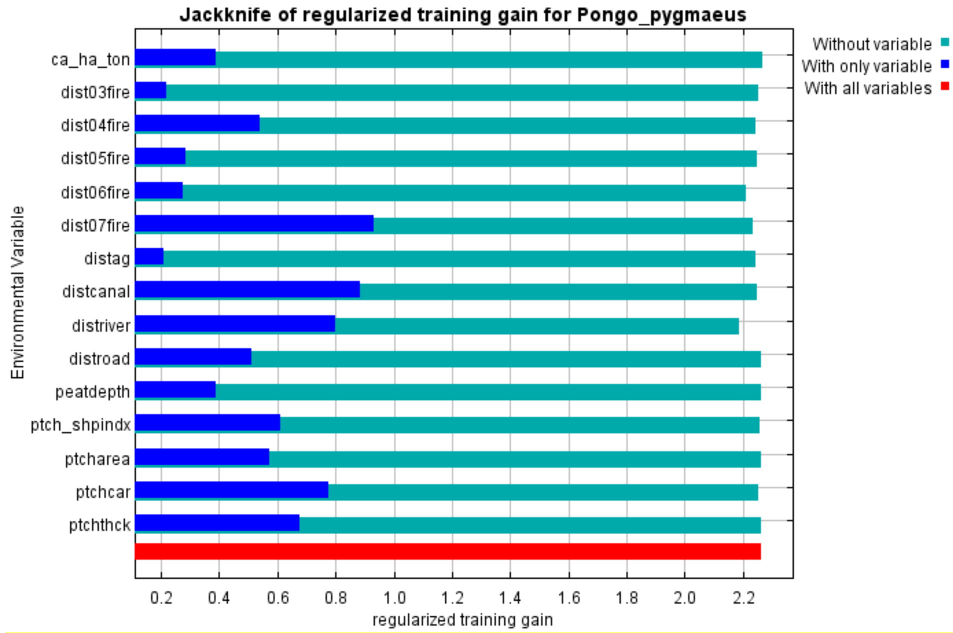

Figure 9. Jackknife test of variable importance produced by *Maxent* .

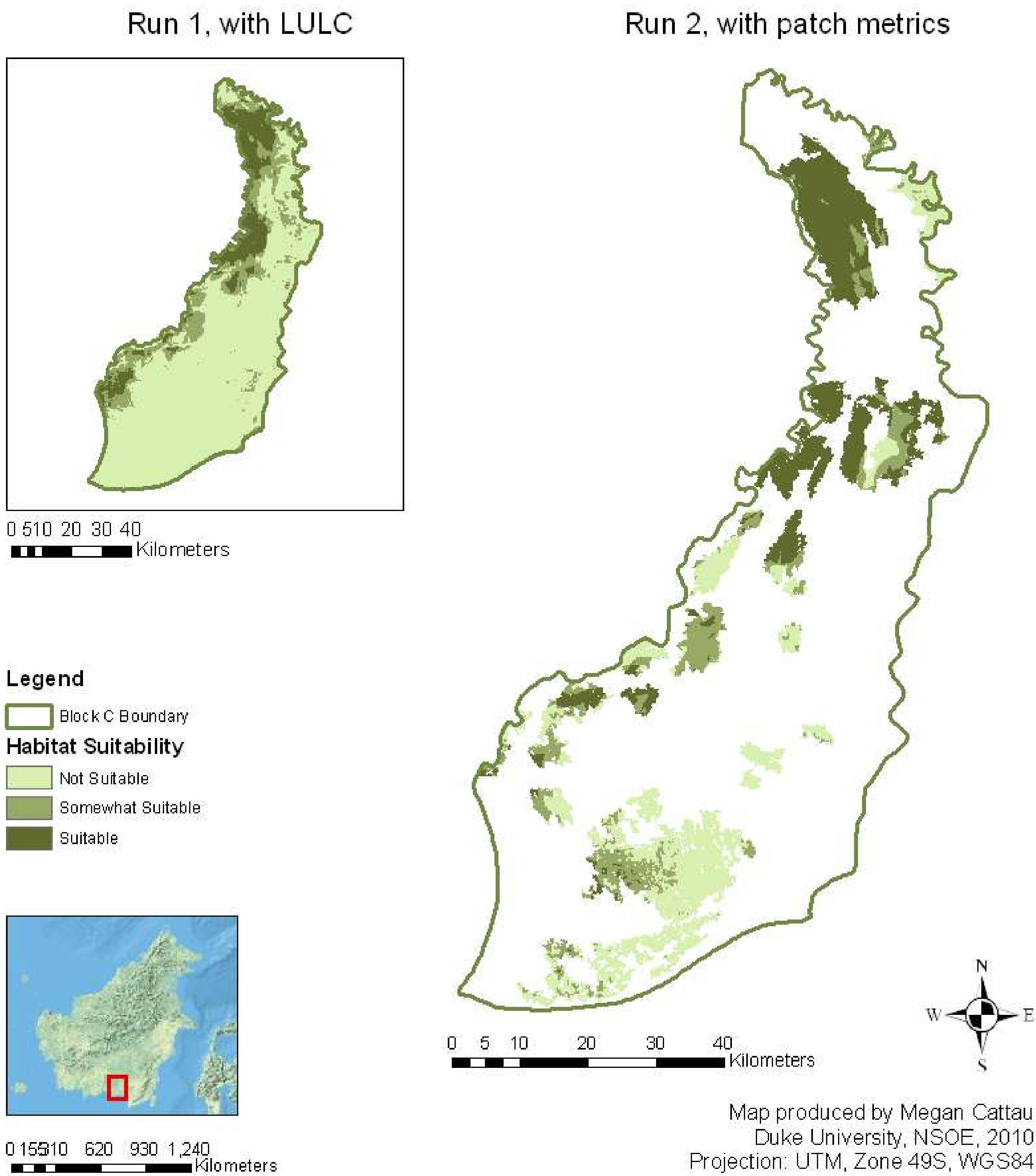

Figure 10. ***Maxent*** **Species Distribution Model.**

Corridors

The ideal corridor path identified between patches 3 and 13 using the SDM as the cost surface also included priority patches 6 and 8, as well as patches 7, 9, and 11 (Figure 11). The corridor path between patches 13 and 24 did not include any other patches. If we consider patch 2 to be connected to patch 3, these corridors would allow patches 9 patches to be functionally connected in terms of orang-utan dispersal, increasing the viable population size on Block C from 1,146 individuals to 1,660.

The corridor path identified between patches 3 and 13 using the combined SDM and carbon value as the cost surface included priority patches 6 and 8 and patches 7, 9, and 11, just as the analysis completed with the SDM cost surface. However, because the corridor path followed high-carbon value areas further to the west, it also included patch 10. Likewise, the corridor path between patches 13 and 24 was located more to the west than the path found using the SDM cost surface, and so it included two additional patches, patches 17 and 23. With these three additional patches included in the functional network, the viable population size on Block C is further increased to 1,788 individuals if the carbon value is considered.

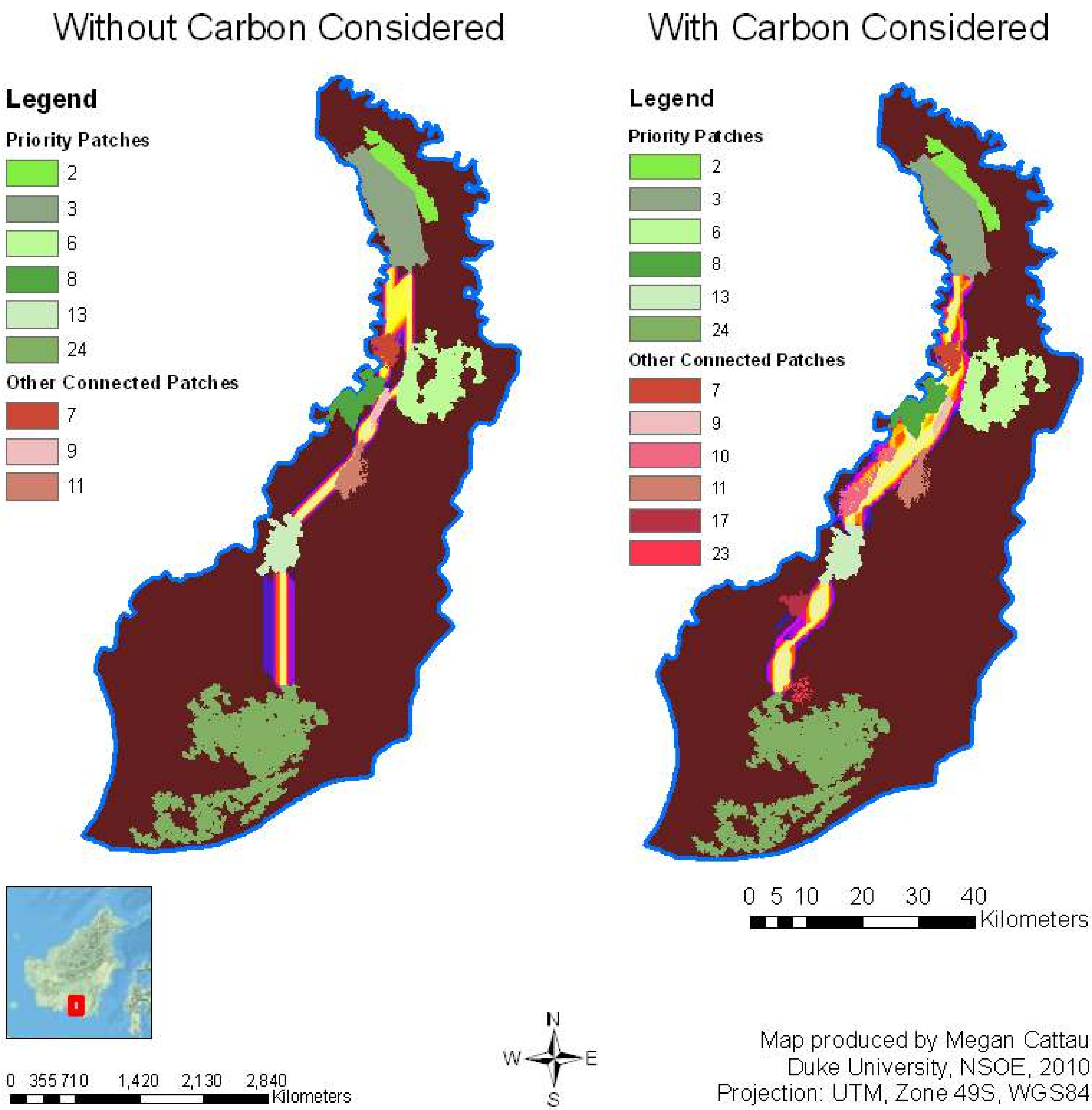

Figure 11. Corridor Paths between habitat patches without and with carbon value considered.

Discussion

The density, distribution, and abundance of Bornean orang-utans on Block C of the Former Mega Rice Project was formerly unknown. This information, produced in this project, will contribute to the body of knowledge concerning this understudied population and will allow for more accurately focused conservation efforts for these orang-utans. Additionally, I have identified which existing fragments of habitat are most vital for the population of orang-utans on Block C and highlighted potential corridor paths between priority habitat patches. Efforts are currently being made to restore degraded hydrology and forest on Block C, which will prevent further peatland oxidation, increase the land's ability to sequester carbon, retard the detrimental peatland fires that have been occurring there since the 1990s, and increase the quality of the forest for the resident population of orang-utans. The analyses completed in this study will increase the chances that conservation and restoration activities currently being undertaken on Block C will actually benefit the viability of the orang-utan population living there by forming a functional network for the population. Additionally, the incorporation of the carbon value of the land into this study allows for orang-utan conservation plans that are more economically feasible in this area.

Some additional information would greatly benefit the accuracy of the study. First, Boehm and Siegert (1999) indicate that intensive ground truth checking is necessary for an accurate impression of a landscape from satellite data. However, in this case, I was not able to obtain many ground truth points or an accurate map against which to compare the data that I classified. Additionally, some of the southern area is distorted by cloud shadow that could not be masked out and, thus, may be incorrectly classified. However, those details are somewhat negligible in this case, as I was analyzing peatforest fragments, whose spectral signature was significantly easier to discern than that of the other land cover classes. Thus, even without ground data or an accuracy assessment, I feel fairly confident with my success in isolating PSF from other land cover types. Although the largest fragment, patch 24, was somewhat distorted by clouds, this did not have a significant effect on the analysis. The masked-out clouds covering this patch would make the patch appear less condensed than it may be in reality, but it was still considered one of the priority patches despite this potential distortion.

Additionally, some of the thresholds chosen for the analysis were somewhat subjective. For example, the 350 ha threshold selected for minimum orang-utan habitat patch sizes, although based on range requirements for female orang-utans, did not consider several additional factors. Specifically, male orang-utan ranges are noted to be several times larger than female home ranges, but little data is available on the actual area required. Male ranges are also not exclusive or stable (van Schaik & van Hooff, 1996). Thus, the connectivity of habitat patches becomes especially important for male dispersal and the resulting genetic variation in individuals and metapopulations across the landscape. Also, the weighting of the patches based on patch geometry metrics is a source of uncertainty. Little data is available concerning the response of orang-utan populations to the patch geometry metrics calculated. Patch area was given the most importance because most conservation planners appreciate the relative importance of patch area for species protection (Margules and Pressey, 2000). However, other metrics have been shown to be important determinants of species presence (Helzer and Jelinski, 1999). More research is required in this regard.

If the trends of lowland peatswamp forest loss in Indonesia continue, then the ability of the area to support orang-utans and other species or to mitigate global climate change does not appear hopeful. A report by the Indonesian Ministry of Forestry in co-operation with the European Union states that the world demand for palm oil is projected to increase twofold by 2020, and that they predict "that by far the largest slice of this new land will come from within Indonesia where labour and land remain plentiful. It is inevitable that most new oil palm will be in the wetlands, as the more 'desirable' dry lands of the island are now occupied," (Sargeant, 2001). If the agricultural development pressures promised above by this report come to pass, then the fate of peatswamp forests all over Indonesia appears grim. However, I believe that the incorporation of the carbon value of the land into land management decisions could change that. Additionally, in terms of orang-utan conservation specifically, I expect that the land most suitable for orang-utans will also have the highest value on the carbon market, as both orang-utan densities and carbon storage are high in areas of deep peat.

This has great implications for the economic feasibility of orang-utan conservation through the preservation of intact habitat patches and through the establishment of corridors that connect existing populations. More research is needed concerning the potential to incorporate carbon value into land management decisions and protection area establishment throughout tropical peatswamp forest areas. Just as spatially explicit analysis is required for effective species conservation planning, sight-specific economic valuation of the opportunity cost of conservation will also be required. Venter et al. (2009b) estimate that payments for REDD at USD 10-33 per tonne of CO_2 (USD 2-16 per tonne if cost-efficient areas are targeted) could feasibly offset the opportunity costs of forest protection in Kalimantan, Indonesia. On the other hand, Butler et al. (2009) argue that REDD will not be able to compete with clearing land for palm oil in Indonesia unless it is incorporated into the compliance market, which would boost the profitability of forest conservation. Over the next 25 years, 3,750–5,400 tonnes of CO_2 will be emitted for each hectare of peatland developed for oil palm (Pearce, 2007). Also, if the oil palm is used for biofuel, this will result in 25–36 times more CO_2 emitted from the peatland as would be saved from vehicle emissions (Yule, 2010). There is hope for inaccessible areas like the former Mega-Rice project in particular, where opportunity costs of conservation still remain relatively low.

Putz and Redfore (2009) mention concerns about carbon-based conservation, stating that silvicultural interventions intended to boost carbon stock could have adverse effects on biodiversity. Because biodiversity and other ecosystem services will not automatically and collaterally benefit from REDD and its preservation of carbon stocks, it is important to prioritize areas that can have multiple benefits on the ground

(Miles and Kapos, 2008). This project has demonstrated how carbon projects can be planned so that co-benefits are explicitly targeted and benefits are maximized on the landscape (Venter et al., 2009a). However, for this to be successfully reproduced in other areas, planning will necessarily be site-specific and spatially explicit.

Additionally, one of the greatest challenges in implementing a biodiversity-centered approach to carbon market projects will be institutional capacity. There will need to be support on the regional and national level to ensure that biodiversity is considered in carbon projects intended for the compliance market. Currently, under the voluntary framework, CCB Standards and similar standards ensure that the biodiversity and community livelihood co-benefits are present in a project. For example, the first REDD project that met the CCBS was the Ulu Masen Project, which protected a large area of peatswamp forest in Sumatra from being converted into palm oil, while protecting biodiversity and promoting the livelihood of local communities. To ensure net positive biodiversity benefits for climate mitigation projects in the compliance market, this will likely need to be incentivized or required.

This project demonstrates how we might use carbon financing to make possible not just forest preservation and restoration, but also wildlife protection strategies. The carbon funding mechanisms of REDD and CDM could be successfully used to preserve and connect intact forest fragments in single-species or biodiversity conservation strategies if the co-benefits of carbon projects are appropriately valued.

Literature Cited

Aldhous, P. 2004. Land remediation: Borneo is burning. Nature. 432: 144-146.

Ancrenaz, M., Gimenez, O., Ambu, L., Ancrenaz, K., Andau, P., Goossens, B., Payne, J., Tuuga, A., and Lackman-Ancrenaz, I. 2005. Aerial surveys give new estimates for orang-utans in Sabah, Malaysia. Public Library of Science Biology. 3(1): 30-37.

Ancrenaz, M., Lackman-Ancrenaz, I. and Elahan, H. 2006. Seed spitting and seed swallowing by wild orang-utans (*Pongo pygmaeus morio*) in Sabah, Malaysia. Journal of Tropical Biology and Conservation. 2(1): 65-7.

Ancrenaz, M., Marshall, A., Goossens, B., van Schaik, C., Sugardjito, J., Gumal, M. and Wich, S. 2008. *Pongo pygmaeus*. In: IUCN 2010. IUCN Red List of Threatened Species. Version 2010.1. <www.iucnredlist.org>. Downloaded on 25 February 2010.

Boehm, H. D. V., and Siegert, F. 1999. Application of Remote Sensing and GIS to survey and evaluate tropical peat. Kalteng Consultants. International Conference and Workshop on Tropical Peat Swamps, Safeguarding a Global Natural Resource. 27-29 July 1999. Penang, Malaysia.

Buckland, S.T., Anderson, D.R., Burnham, K.P., and Laake, J.L. 1993. Distance Sampling—Estimating Abundance of Biological Populations. Chapman and Hall, London.

Butler R. A., Koh L. P. and Ghazoul J. 2009. REDD in the red: palm oil could undermine carbon payment schemes. Conservation Letters. 2: 67-73.

Copenhagen Accord, Draft decision. 2009. Conference of the Parties, Fifteenth Session. 1-5. Copenhagen: United Nations Framework Convention on Climate Change.

Crist, E.P. and Kauth, R.J. 1986. The tasseled cap de-mystified. PEERS 52(1):81-86.

Elith, J., Graham, C.H., Anderson, R.P., Dudik, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., Li, J., Lohmann, L., Loiselle, B.A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J.M., Peterson, A.T., Phillips, S., Richardson, K., Schachetti Pereira, R., Schapire, R.E., Soberón, J., Williams, S.E., Wisz, M. and Zimmermann, N.E. 2006. Novel methods improve predictions of species' distributions from occurrence data. Ecography. 29 (2): 129–151.

ESRI. 2008. ArcGIS v.9.3. Redlands, CA.

Galdikas, B. M. F. 1988. Orang-utan diet, range and activity at Tanjung Putting, Central Borneo. International Journal of Primatology. 9:1-35.

Goossens, B., Chikhi, L., Ancrenaz, M., Lackman-Ancrenaz, I., Andau, P., and Bruford, M.W. 2006. Genetic Signature of Anthropogenic Population Collapse in Orang-utans. PLoS Biol 4(2): e25 doi:10.1371/journal.pbio.0040025.

Helzer, C. and Jelinski, D. E. 1999. The Relative Importance of Patch Area and Perimeter-Area Ratio to Grassland Breeding Birds. Ecological Applications. 9(4): 1448-1458.

Hooijer, A., Silvius, M., Wösten, H. and Page, S. 2006. PEAT-CO2, Assessment of CO2 emissions from drained peatlands in SE Asia. Delft Hydraulics report Q3943.

Husson, S. J., Wich, S. A., Marshall, A. J., Dennis, R. D., Ancrenaz, M., Brassey, R., gumal, M., Hearn, A. J., Meijaard, E., Simorangkir, T., and Singleton, I. 2008. Chapter 6, Orang-utan distribution, density, abundance and impacts of disturbance. In S Wich, S. A., Utami Atmoko, S. S., and Setia, T. M. *Orang-utans*. 77-97. Oxford Scholarship Online Monographs.

Jaynes, E. T., 1990. Notes on present status and future prospects. In: Grandy Jr., W.T., Schick, L.H. (Eds.), Maximum Entropy and Bayesian Methods. Kluwer, Dordrecht, The Netherlands, 1–13.

Margules, C. R. and Pressey, R. L. 2000. Systematic conservation planning. Nature. 405: 243-253.

McCune, B., and Grace, J. B. 2002. Analysis of ecological communities. MjM Software Design, Gleneden Beach, Oregon.

Miles, L. and Kapos, V. 2008. Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation: Global Land-Use Implications. Science. 320: 1454-1455.

Minnemeyer, S., Boisrobert, L., Stolle, Muliastra, F., Y. I. K. D., Hansen, M., Arunarwati, B., Prawijiwuri, G., Purwanto, J., and Awaliyan, R. 2009. Interactive Atlas of Indonesia's Forests (CD-ROM). World Resources Institute: Washington, DC.

Morrogh-Bernard, H., Husson, S., Page, S. E., and Rieley, J.O. 2003. Population status of the Bornean orang-utan (*Pongo pygmaeus*) in the Sebangau peat swamp forest, Central Kalimantan, Indonesia. Biological Conservation. 110: 141-152.

Murray, B., Lubowski, R., and Sohngen, B. 2009. Including International Forest Carbon Incentives in Climate Policy: Understanding the Economics. Duke University and the Nicholas Institute for Environmental Policy Solutions. Durham, NC: Nicholas Institute.

Pearce, F. 2007. Bog barons: Indonesia's carbon catastrophe. New Scientist. 2632:50–53.

Phillips, S. J., Anderson, R. P., and Schapire, R. E. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modeling. 190: 231-259.

The Provincial Government of Nanggroe Aceh Darussalam, Fauna & Flora International (FFI), and Carbon Conservation Pty. Ltd. 2007. Reducing Carbon Emissions from Deforestation in the Ulu Masen Ecosystem, Aceh, Indonesia (A Triple-Benefit Project Design Note for CCBA Audit).

Putz, F.E. and Redfore, K.H. 2009. Dangers of carbon-based conservation. Global Environmental Change. 19: 400-401.

Rijksen, H.D. and Meijaard, E. 1999. Our Vanishing Relative: The Status of Wild Orang-utans at the Close of the Twentieth Century. Dordrecht: Kluwer Academic Publishers.

Sargeant, H.J. 2001. Oil palm agriculture in the wetlands of Sumatra: destruction or development? Report, Forest fire prevention and control project; Government of Indonesia Ministry of Forestry & European Union.

Singleton I., Wich S. A., Husson S., Stephens S., Utami-Atmoro S. S., Leighton M., Rosen N., Traylor-Holzer K., Lacy R. C. and Byers O. 2004. Orang-utan Population and Habitat Viability Assessment: Final Report. IUCN/SSC Conservation Breeding Specialist Group. Apple Valley, MN.

Stern, N. 2006. Stern Review of the Economics of Climate Change.

Thomas, L., Laake, J.L., Derry, J.F., Buckland, S.T., Borchers, D.L., Burnham, K.P., Strindberg, S., Hedley, S.L., Burt, M.L., Marques, F., Pollard, J.H., and Fewster, R.M. 1998. DISTANCE 3.5. Research Unit for Wildlife Population Assessment, University of St Andrews, UK.

van Schaik, C. P. and van Hooff, J.A.R.A.M. 1996. Toward an understanding of the orang-utan's social system. From *Great Ape Societies*. McGrew, W. C., Merchant, L. F., and Nishida, T., eds.

Venter, O., Laurance, W.F., Iwamura, T., Wilson, K.A., Fuller, R. A., and Possingham, H.P. 2009a. Harnessing Carbon Payments to Protect Biodiversity. Science. 326: 1368.

Venter O., Meijaard E., Possingham H., Dennis R., Sheil D., Wich S., Hovani L. and Wilson K. 2009b. Carbon payments as safeguard for threatened tropical mammals Conservation Letters. 2:123-129.

Yeager, C.P. 1999. Fire impacts on vegetational diversity and abundance in Kalimantan, Indonesia during 1997/1998. WWF-Indonesia report, Jakarta.

Yeager, C.P. and Fredriksson, G. 1999. Fire impacts on Primates and other wildlife in Kalimantan, Indonesia during 1997/1998. WWF-Indonesia report, Jakarta. WWF-Indonesia report, Jakarta.

Yule, C.M. 2010. Loss of biodiversity and ecosystem functioning in Indo-Malayan peat swamp forests. Biodiversity and Conservation. 19:393-409.

Appendix A: Radiometric and Atmospheric Correction of Satellite Data

I converted the L1G files to units of reflectance upon import in order to reduce scene variability between images by first converting the DNs to units of absolute spectral radiance, measured in watts per square meter per steradian (W/ m^2/ sr), using 32-bit floating point calculations. The following equation is used to convert DNs in a L1G product back to radiance units:

*Radiance = gain * DN + offset*

which is also expressed as:

$$\text{Radiance} = \left(\frac{\text{LMAX} - \text{LMIN}}{\text{QCALMAX} - \text{QCALMIN}}\right)(\text{DN} - \text{QCALMIN}) + \text{LMIN}$$

where,

LMAX is the maximum achievable spectral radiances for each band at digital number QCALMAX respectively,

LMIN is the minimum achievable spectral radiances for each band at digital number QCALMIN respectively,

QCALMAX is the maximum DN value (for example 255),

QCALMIN is the minimum DN value (for example 0 or 1).

Then, normalization for solar irradiance was completed by converting spectral radiance, as calculated above, to planetary reflectance or albedo. This combined surface and atmospheric reflectance of the Earth was computed with the following formula:

$$\rho_P = \frac{\pi \cdot L_\lambda \cdot d^2}{Esun_\lambda \cdot \cos\theta_S}$$

where,

ρ_P= unitless effect planetary reflectance

L_λ= spectral radiance at the sensor's aperture

d= Earth-Sun distance in astronomical units

$Esun_\lambda$= Mean solar exoatmospheric irradiances

θ_S = Solar zenith angle

Current values for θ_s are specified in the SUN_ELEVATION record, which was found in the LPGS_Metadata file.

The value for d is calculated by the formula:

$$d = 1 - 0.01672\{\cos[0.9856(JulianDay - 4)]\}(\pi/180)$$

Appendix B: Variables Used in Maxent Distribution Model

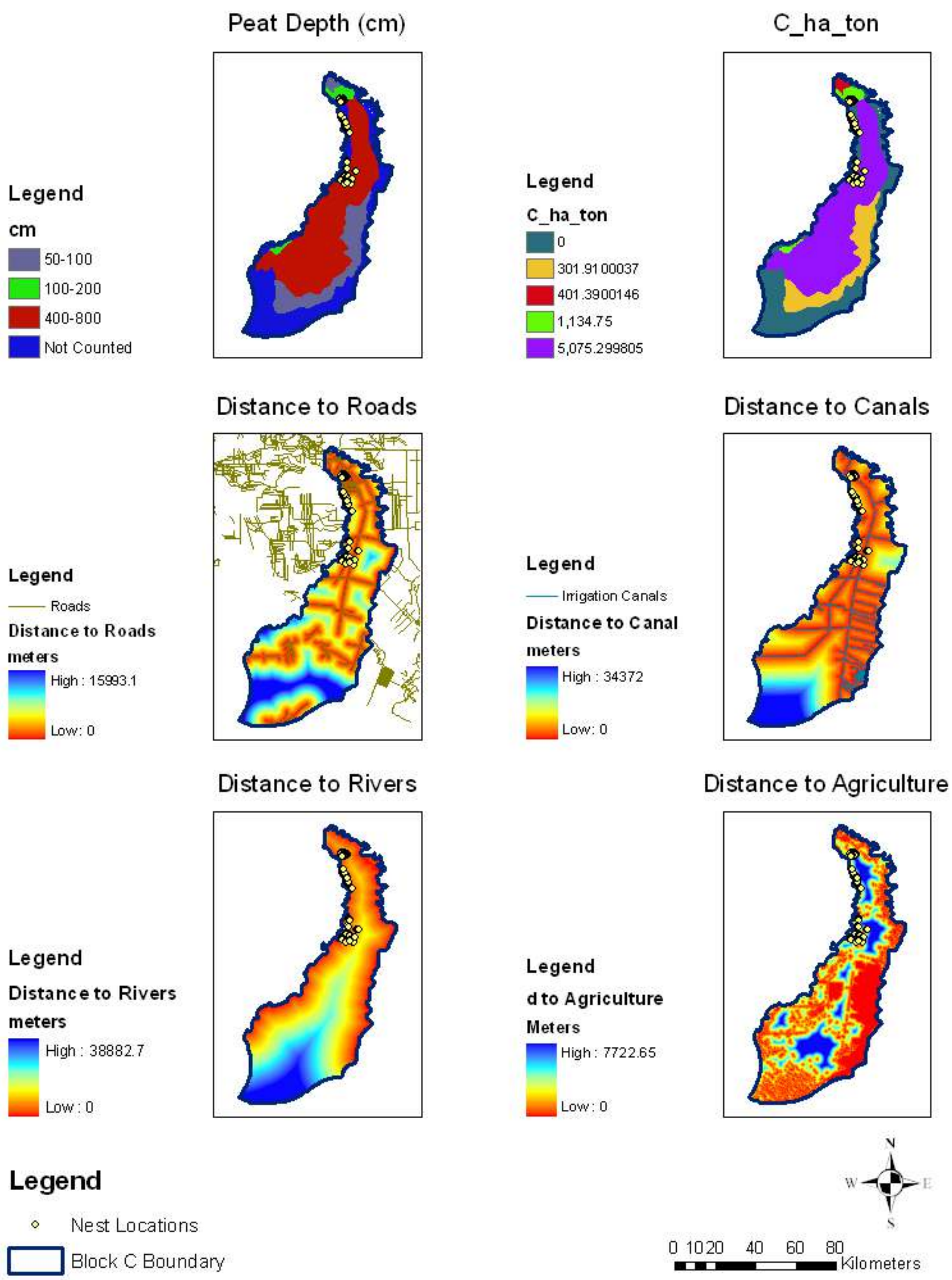

Figure 12. Six of the predictor variables entered into the *Maxent* model.

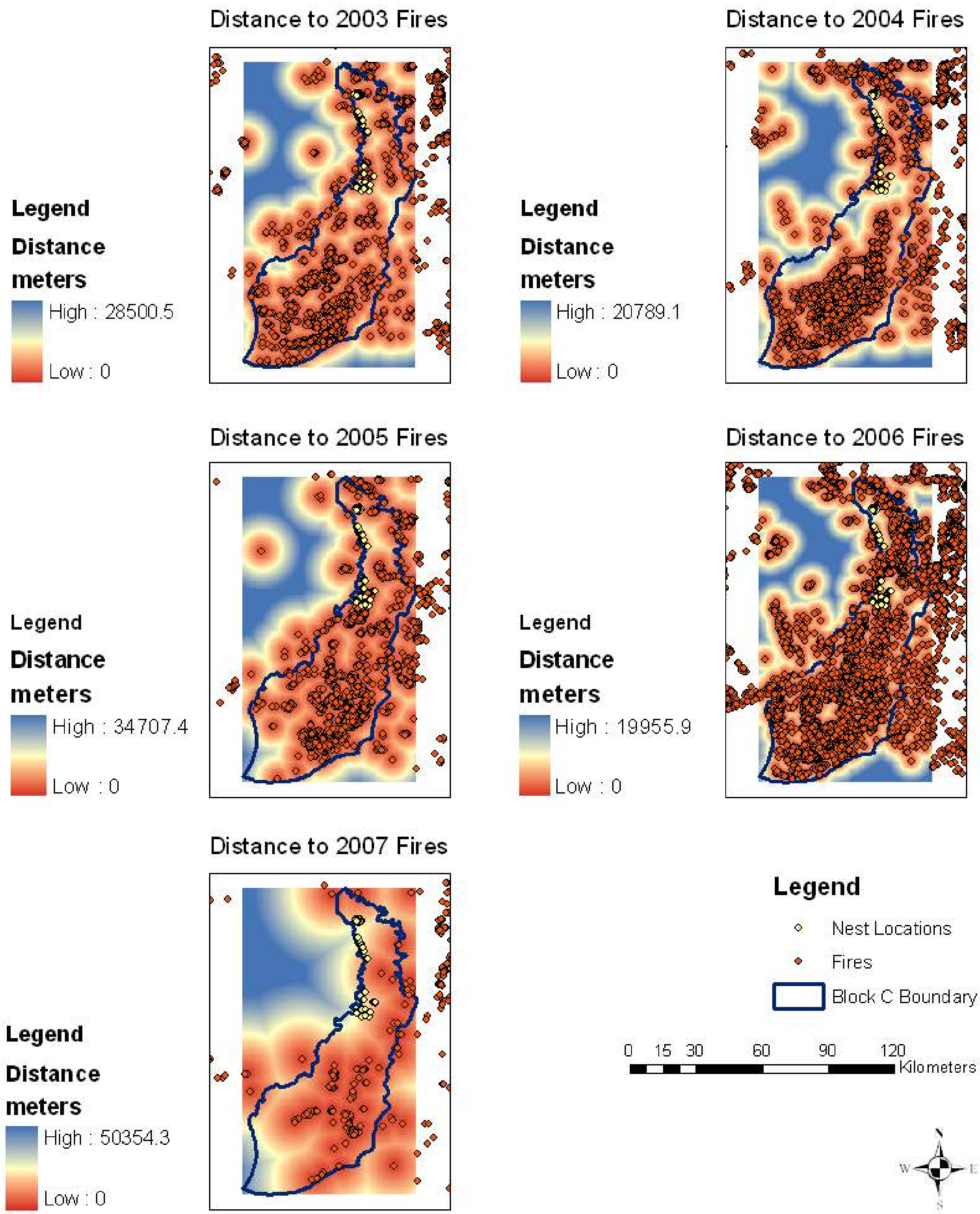

Figure 13. Five of the predictor variables entered into the *Maxent* model.