

# **A STATISTICAL APPROACH TO TIPPING POINT IN DEGRADATION OF MANGROVE AREAS IN MUMBAI, INDIA**

SIDDHI MUNDE  
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SUPERVISORS:

Prof. Dr. Ir. Alfred Stein  
Ms Dr. Ir. Wietske Bijker



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## **SUPERVISORS:**

Prof. Dr. Ir. Alfred Stein  
Ms Dr. Ir. Wietske Bijker

## **THESIS ASSESSMENT BOARD:**

Prof. Dr. Ir. M.G. Vosselman (chair)  
Dr. Ing. G. Polder, Wageningen UR

#### Disclaimer

This document describes work undertaken as part of a programme of study at the Faculty of Geo-information Science and Earth Observation of the University of Twente. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the Faculty.

## ABSTRACT

Tipping point is a critical threshold leading to a new state in a system. A formal method for direct identification of tipping points is not defined. This research explores how to integrate a statistical method for identify tipping point. Additionally, due to the spatial patterns exhibiting more information about the causes and effect, analysis in explicit spatial context for finding tipping point is necessary. Degradation process in mangrove forest was selected as case study. Four sites exhibiting different degradation levels in Mumbai, India were included in the study. Point pattern analysis was used as a general approach for identification of tipping points. Canopy gaps as a measure for degradation and point pattern related to it for statistical analysis were measured using remote sensing techniques. A new summary statistic, J function for heterogeneous process, and a causal model, using fitting of the Strauss model with explanatory variable was part of the statistical analysis. Inferences for degradation being related to interaction were known. The results show partial relation of interaction to degradation, with a planar point pattern. A complete causal model for the observed point pattern was not obtained and further modifications to this model are suggested.

### Keywords

*Tipping point, Mangrove degradation, Forest Canopy Density, Inhomogeneous J-function*

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## Chapter 1

# Introduction

The term tipping point was popularized by the works of Gladwell (2006) in the context of socio-logical situations experienced in daily life. It is described as a moment of critical mass, a threshold or a boiling point. Scheffer et al. (2009) in general, called a tipping point as critical threshold and in terms of complex model as a bifurcation point (Scheffer et al., 2001). The tipping point occurs when a system shifts abruptly from one state into another. This brings about qualitative and quantitative changes in the properties and state of the system, which may be a point of no return. This concept was adapted in other studies as an instance when a perceptible change occurs after a relatively small event (Wassmann & Lenton, 2012; Lenton, 2012).

Early warning signals are used to study tipping point. They are generic symptoms just before any shift occurs in the system indicating a tipping point. (Van Nes & Scheffer, 2007) introduced critical slow down as an indicator of tipping point. Critical slow down is the reduction in recovery rate due to approaching tipping point. Other statistical indicators such as variance, skewness, auto correlation and spatial correlation were stated related to tipping point (Carpenter & Brock, 2006; Guttal & Jayaprakash, 2008; Dakos et al., 2008; Dakos, van Nes, Donangelo, Fort, & Scheffer, 2010). However, the properties and the condition under which tipping point can be known is still unclear (Drake & Griffen, 2010).

Analysis of tipping point for degradation process in mangroves can be conducted in three ways: time series analysis, spatial analysis and spatio-temporal analysis. Time series and spatio-temporal analysis are governed by the need of large time series data. This motivates research towards explicit spatial analysis for degradation of mangrove forest for the tipping point. Furthermore, spatial patterns are capable of exhibiting more information about the process than by an instance in time series (Scheffer et al., 2009).

Tipping points can be studied only in spatial context. Spatial patterns can be an indication of critical transition (Scheffer et al., 2009). Spatial patterns exhibit typical trends in distribution of events in space. Therefore, spatial analysis for trend or pattern as a state of the system and identification will be helpful to identify approaching tipping point. For spatial patterns related to the tipping point, properties like patch-size distribution (Kéfi et al., 2007) and self-organised patchiness (Rietkerk et al., 2004) was studied. However, identifying patterns for real data is difficult and needs explicit exploratory analysis since it differs from study to study.

Mangrove ecosystem are the most complex and dynamic ecosystem in the environment (Kathiresan, 2002). They are a transition ecosystem between coastal and terrestrial environments. They consists of salt tolerant species of trees and are breeding ground for aquatic organisms. This dependence increases its importance for study and conservation to prevent instability in the environmental cycle. Due to the current global climate change situation and occurrence of unanticipated extreme events of cyclones and tsunamis the importance of mangroves has been raised. This has lead to change in perception about mangroves and have directed towards global conservation methods.

Mumbai, India, is one of the mega-cities in the world with a population of over 13 million. This region comprises of the main city and its suburbs. It lies on the western coast of India and is the

commercial capital of India. As other mega cities around the world, environmental conservation is one of the challenges faced by this city due extensive air and water pollution. This has severely affected the mangrove forests around this region resulting in major loss of mangrove in past two decades(DasGupta & Shaw, 2013). Some species of mangroves around Mumbai are on verge of extinction due to excessive degradation, leading to loss of biodiversity.

Fragmented vegetation pattern exists in degraded mangrove forests. Ecologically, the vegetation pattern of degraded mangroves partly governs the dynamics of tree development including competition, growth, mortality, and regeneration(Kathiresan, 2002). Analysing these spatial patterns can therefore be of major ecological interest, particularly with regard to the prediction and anticipation for long-term conservative measures. Advanced statistical methods which are capable of analysing spatial patterns with the concept of tipping point to anticipate the collapse in mangroves, gives a promising start for research in this direction.

Tipping point stands for change and also has the potential to lead to intelligent actions. This concept of the tipping point has been highlighted as a bridge between science and policy makers (Werners et al., 2013). However, more research about such thresholds related to the change observed in its system is required to lead to efficient decision making.

Study of tipping point for degradation of mangroves is essential. They are thus extremely vulnerable to collapse, leading to permanent loss of these forests and threat to other related ecosystems. In addition, mangroves around this city are degraded, but the level is not known. The study of tipping point for mangrove can help to identify the current status of the mangroves around this city and identify the drivers for conservation policies. This study thus aims to introduce an integration of the statistical tipping point with the degradation process in mangrove forest through the means of remote sensing.

## 1.1 RESEARCH OBJECTIVES

1. To identify the causes, variables and indicators that could represent degradation in mangrove forests
2. To measure the variables and their variation to identify probable threshold values for tipping points at different locations in the study area.
3. To identify an appropriate statistical model for tipping points, applicable to degradation in mangrove forest.
4. To validate the applicability of the model for the tipping point by comparing with other mangrove forests location.

## 1.2 RESEARCH QUESTIONS

1. How are variables incorporated in statistical analysis of degradation in mangrove forests?
2. Can the variables be derived through remote sensing to reflect degradation?
3. How to measure variables for degradation in statistical analysis of tipping point?
4. Which statistical method facilitates the identification of tipping point?
5. What is the relation between the statistical results for different sites?

### 1.3 THESIS OUTLINE

Chapter 2 gives review about the study of tipping point and overview about the mangrove ecosystem. The overall methodology of this research is covered by two chapters. Chapter 3 gives an introduction to mangrove sites and the method followed to measure canopy gaps as points. Point pattern analysis on these points is described as a statistical method for degradation to identify tipping point. The content of chapter 3 is J function and fitting of Strauss model to the point pattern and its implementation. The results for the complete study is presented in Chapter 5 followed by discussion in Chapter 6. The conclusions answering the research questions and recommendation for future work is given in Chapter 7.



## Chapter 2

# Tipping point and mangroves

### 2.1 THE CONCEPT OF TIPPING POINT

#### 2.1.1 Definition

In ecosystem studies, the concept of a tipping point has a generic definition of being a critical point, a bifurcation point or a threshold after which there is an abrupt change in the state of the ecosystem (Scheffer et al., 2001). It is a unifying metaphor, encapsulating a non-linear notion for small and abrupt changes observed in real systems. Wassmann and Lenton (2012) highlights the need for a clear definition and meaning of tipping point to avoid any misunderstanding or false outcomes. For example, in social studies tipping point describes a rare phenomenon becoming dramatically common. Here, the definition of a tipping point should clearly state a broader description which includes non-linear phenomenon in the process under study. The resulting state of the process can be irreversible or reversible depending on the study. Lenton (2012) provides a method to practically understand and achieve this.

Lamberson and Page (2012) introduces a tipping point as a discontinuity between the current and future state of the systems. This is achieved by measures for the system to tip based on the changes in the probability distribution over future states. He also introduces two types of tips, i.e direct tips and contextual tips, to help manage tipping dynamics in any case study. A direct tip occurs when a gradual change in one variable leads to a large change in the same variable in a future state. A contextual tip occurs when a gradual change in one variable leads to large change in some other variable being studied. He concluded that occurrence of tips are driven by changes in variables and environmental shifts. The "direct tips change where system will go, while contextual tips change the set of states where the system can go" (Lamberson & Page, 2012).

A Tipping point for mangroves is a threshold after which there is permanent loss of mangroves. In this case, it is an irreversible state for a mangrove system. The classification of tips in this study can be helpful on basic exploratory analysis of this study. Tipping point can be formally defined in accordance with the typology that was introduced by Lamberson and Page (2012).

#### 2.1.2 Application

The tipping point has mainly been studied in relation to the detection of early warning signals and bifurcation theory. Scheffer et al. (2009) explained early warning signals before the critical threshold, when the tipping point occurs. The author explains about catastrophic bifurcation, where the system after the critical point is propelled through a directional change to a contrasting state and critical slowing down. This phenomenon of critical slow down leads to three possible early warning signals for approaching a bifurcation point: slow recovery from disturbance, increased autocorrelation and variance in the pattern of fluctuation. They are generic symptoms or properties observed in the transition that is approaching tipping point. Apart from these properties, skewness and flickering phenomenon in the state of the system can be observed before the bifurcation when the amplitude of disturbances is high enough. Spatial patterns can be used as early

warning signal before critical transition by studying the characteristic change of distributed units in the system when external force or disturbances occur.

Statistical measurement that were used as early warning signals fail in some cases due to local conditions. This was concluded by Boulton et al. (2013) when early warning signals of approaching tipping point were being identified for die back phenomena in the Amazon forest. In this case, the key indicator of auto-correlation was missing and the increment in variance did not relate to the loss of forest cover. The author relate the failure in identifying the tipping point with two reason. First, there was no critical transition and secondly the model that was used for studying was so simplified that it could not capture the rapid and non-linear force that leads to critical transition. The critical point was missed and auto-correlation was eliminated. Further research at finer spatial scale is thus recommended. A conceptual model is defined by Wassmann and Lenton (2012) for tipping point when the system switches between two regimes.

Carstensen and Weydmann (2012) proposed a statistical analysis of the changes in statistical properties of the data. They were able to observe evidence of a tipping point by analysing the mean and variance of data distribution. This suggests that changes in the mean and standard errors of the distribution may manifest the presence of a tipping point. Hence, a tipping point can be found in different kinds of responses (mainly due to local conditions), and all properties of the data should be thoroughly examined for the possible evidence of a tipping point.

Several studies suggest the use of mathematical theories in application of the tipping point. Guns et al. (2012) suggested that a single maximum in a F-score curve can be referred to as the tipping point. F-score is one of the best known measures of information retrieval where maximum information is retrieved at a single 'ideal' in terms of F-score. It is a function of retrieved items having a distinct shape and a clear maximum, a tipping point. "On S-curves and tipping points" (2007) proposed the use of S-curves for identification of tipping point. The knee on a growth curve and tipping point both refer to a point where growth accelerates dramatically. Therefore, it is suggested that tipping point can be explored in growth curves using a dynamic 3-parameter model. Kuehn (2011) gives an overview of the standard mathematical theories that can be applied for identification of critical transitions. This method focus on identification of properties related to early warning signals that lead to critical transitions.

## 2.2 MANGROVES

Mangroves are marginal ecosystems found on the edges of land and sea interfaces (Tomlinson, 1994). Mangrove forests are comprised of salt tolerant trees located in intertidal zones and its adjacent regions. They are well adapted to survive variable environmental conditions and adapt to extreme conditions. They are found in tropical coastal regions like deltas and estuaries. Six different types of mangrove forests can be distinguish when considering their coastal settings. The type of coasts and other ecological characteristics like tidal gradient, temperature, salinity, fresh water supply and sediment characteristics are responsible for the formation of mangrove habitat and details can be found in Tomlinson (1994); Blasco et al. (2005). In addition, two major elements, Nitrogen and Phosphate are of great significance in the growth of mangroves (Kathiresan & Bingham, 2001).

Mangrove ecosystems are unique, and characterized by highly complex and dynamic relationships due to rich and diverse fauna. They provide shelter for terrestrial and marine species. Above water, the trees and its canopies provide habitat for many species of birds, mammals and reptiles; inside the water, epibiont species exists along with other infaunal and epifaunal species (Nagelkerken et al., 2008). It is also a breeding ground for crabs and fish. Mangrove ecosystems are counted amongst one of the most productive. For example, they provide an array of ecosystem services

like fisheries, and fuel from timber and coastal protection from floods and cyclones.

### **2.2.1 Degradation in mangroves**

Degradation literally means wearing down of surfaces due to any erosive action. In ecology, degradation is deterioration through depletion of resources responsible for its survival, leading to destruction of ecosystems or wildlife. Degradation in mangroves is loss of trees due to a number of causes. The remaining of this section gives details about the causes and effects of degradation process in mangrove ecosystem. Canopy structure in mangroves is a result of deterministic and opportunistic development process of mangrove growth and existence and thus can be studied for understanding the underlying degradation process.

#### **Causes of degradation**

The distribution of mangrove comprises of complex ecological structure with numerous factors influencing the formation and degradation process. Therefore, the effect of degradation differs between different habitats. Urban development, shrimp farming and exploitation of mangrove resources have been the main factors that trigger degradation. Some studies suggest that socio-economic factors like population literacy and level of income have been related to mangrove degradation (Ludwig et al., 2009). Kathiresan (2002) lists stress factors responsible for degradation with physiochemical and biological aspects of degrading and luxuriant mangrove habitat specific to the study area.

#### **Effects of degradation**

Mangrove forests have a natural development cycle which is described by Duke (2001). This cycle includes four stages of the forest development: colonisation, early development, maturity and senescence. According to this cycle, during colonisation natural gaps are formed in canopy due to tree death. After a period of time, gaps are filled with growth of new seedlings which is called turnover to colonisation stage. This is called as the gap recovery process.

Damage to the mangrove forests most commonly result into gaps in the canopy (Duke, 2001). Mangrove gaps commonly of circular cluster with 20-30 dead trees. Young gaps and closed old gaps can be differentiated by stem size and stand density, based on the turnover of forests in the development cycle. Mangrove forest will collapse in case of severe and frequent disturbances due to the previously mentioned causes for degradation.

Ludwig et al. (2009) explained the effect of degradation on biodiversity in mangrove species. In general, mangroves have very low diversity with just 70 true mangrove species present today all around the world. High precipitation and higher mangrove results into more diversity of species in mangroves. However, temperature and length of coastline are also important factors affecting diversity of mangrove species.

### **2.2.2 Regeneration process**

The theory of gap creation and regeneration process is explained by Duke (2001). Gap recovery chiefly depends on the reproductive process (new seeds and seedlings) and vegetative process (lateral spread) in the mangroves. These processes are explained by Tomlinson (1994). In addition, the most common response of mangrove to any perturbation is reiteration. It involves either regeneration of new trunks from previous stems or reorientation of existing stems. Regeneration is usual response in mangroves that depends on availability of stems, which is unequal in species. Vegetative regrowth in disturbed forests is possible from seeds or stems. Though it is believed

that regeneration and vegetative spread is rare under very favourable conditions. Although some species of mangroves have observed to survive (Blasco et al., 2005). These two regenerative processes affect the forest structure and composition. This change in structure is in terms of the canopy and diversity of species. Also, Kathiresan (2002) states that simple formation of canopy gaps changes the physical and chemical characteristics of underlying soil. This affects the growth of seedlings and as well as the type of species growing in the gaps.





## Chapter 3

# Study area and variables

### 3.1 STUDY AREA

The study area for this research includes 4 mangroves sites within and around the city of Mumbai in India. Until 1670, Mumbai formerly known as Bombay) coast comprised of seven islands covered by luxuriant mangroves. Since then, they have been under intense anthropogenic pressure due to urbanization and industrialization. This has resulted into stunted and less dense mangroves Naskar and Mandel (1999). Hence, this region composed of degraded mangrove zones.

FSI (2011) have classified the mangroves around Mumbai as moderately dense and open mangrove. The most common species found here are *Avicennia marina var. acutissima* and *Acanthus ilicifolius*. These species are reported to have a stunted growth and scattered distribution pattern. Some other minor species are found in this region without any distinct zonation patterns.

Figure 3.1 shows four mangrove sites around Mumbai selected for this study. Forests in every location present different stages of degradation. A description of every location is presented below.

Site 1 : Gorai-Manori creek. This creek lies between 19° 11'N 72° 47'E and 19° 15'N 72° 50'E. The total area of mangroves around this creek is 29 km<sup>2</sup>. The downstream region, at the northern bank of the creek, is called Manori and the upstream region is called the Gorai Creek. This region is drained by Dahisar river and experience semidiurnal tides. This provides good tidal flushing, resulting in good coverage of mangroves and abundant mudflats. However, recently this creek has been affected by garbage dumping, sewage disposal, overexploitation by salt industries, fishing, navigation and recreational activities. The region around this creek has thus developed a blended formation of good and degraded mangroves. Due to poor diversity and abundance of species this site has been classified as highly stressed environment(Fernandes et al., 2011).

Site 2: Malad creek. This site lies between 19° 7'N; 72° 47'E and 19° 11'N; 72° 50'E The extent of mangrove forest at this site is approximately 10 km<sup>2</sup>. The mangroves around this site is lost due to intense urban pressure and construction activities along the boundaries. The water quality in this creek is severely affected due to open drains and partially treated sewage from Malad and Versova treatment plants(Vijay et al., 2010).

Site 3: Thane creek. This site is an extensive creek with a big elongated opening to the Arabian sea at its southern end. It lies between 19° 11'N; 72° 59'E and 18° 59'N; 72° 54'E. This site covers an area of 56 km<sup>2</sup>. A large part of this site are covered by mud flats along west bank. These zones are good breeding ground for new seedlings of mangroves. The causes of degradation varies throughout the 26 km long stretch along the coasts from north to south. At the head of the creek is the city of Thane, which is the major source of polluted water into the creek. The industrial zone of Mumbai lies on eastern bank of the creek, which leads to pollution due to industrial effluents.

Site 4: Dharamtar creek. This creek is located south-east of Mumbai near the major industrial

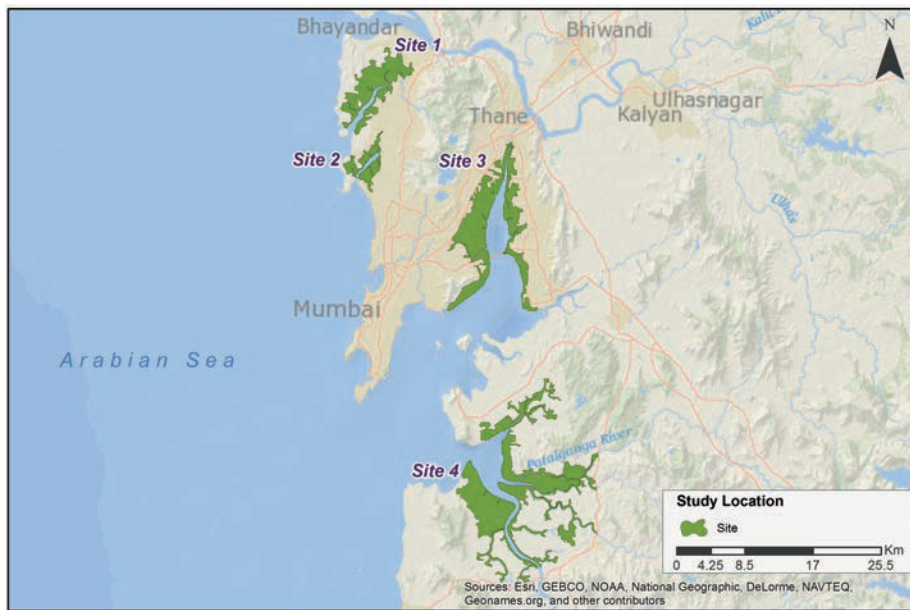


Figure 3.1: Four mangrove sites around Mumbai, India that were selected for the study.

belt of Uran. It is comprised of a main channel and small crisscross sub-creeks. The total area covered by this creek and its sub creeks is around  $89 \text{ km}^2$ . Luxuriant mangroves have been observed in this mid intertidal zone. The mangrove around this creek are mainly affected by sewage, industrial wastes, effluents, maritime activities of Jawaharlal Nehru Port (JNPT) activities and they are extremely vulnerable due to future urban development projects (Pawar, 2013).

### 3.2 VARIABLES FOR DEGRADATION

The state of mangrove can be studied by its canopy structure (Blasco et al., 2005). Canopy density and Leaf Area Index (LAI) are used to study the canopy structure. Calculating LAI is difficult due to its extensive requirement of instrument and fieldwork. Canopy density is taken as an indicator of degradation.

Recent advancement in remote sensing techniques have led to its use for various applications. These techniques have been applied for mangrove mapping using different sensors and indices. However, the choice of sensors and indices in case of mangroves is site specific. Use of Landsat (Green et al., 1998) and band ratios was suggested suitable for identifying mangrove and non-mangrove areas. A method was developed by Roy et al. (1996) to measure Forest Canopy (FCD) by calculating indices from a Landsat-7 image. This method was used in this study and was the basis for further analysis. The following sections describe the selection of variables from canopy density and its measurement.

#### 3.2.1 Selection of variables

Gaps in the canopy are formed due to natural or anthropogenic factors. In natural process, trees grow and these gaps recover to form closed canopies over a period of time. However, they remain as a gap when they cannot recover due to the persisting unfavourable conditions for seedlings to grow. This is due to the underlying degradation process. Figure 3.2 explains natural process and its deviation in case of degradation (Duke, 2001). The open canopy forest remains as the degraded forest. The gaps that remain in this process of degradation can be measured as frequency i.e. number

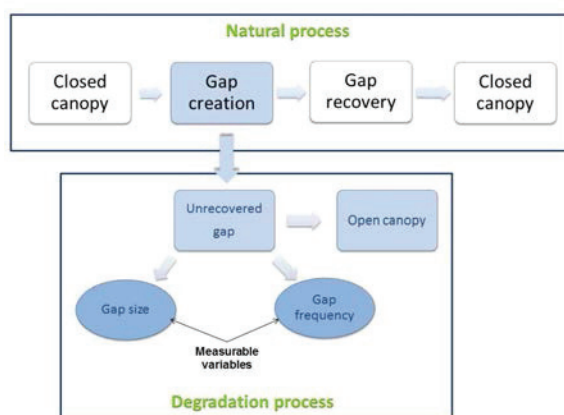


Figure 3.2: The gap dynamics in case of natural and degradation process in mangroves.

of gaps and in size. They are selected as a variable to measure degradation in the mangrove site in this research.

### 3.2.2 Measurement for variables

Study of degradation in terms of canopy gaps is done by converting the gaps into points. However, first forest canopies have to be measured to identify the gaps. This was done in following steps: measure forest canopy with the model from Forest Canopy Density Model(FCD) and identify the gaps to derive point pattern for every mangrove site.

Landsat-8 imagery was used for mapping the mangroves in this study. The imagery was acquired from USGS for April,2013. Landsat-8 in total have 11 bands with spatial resolution of 30 m for bands 1-7. The Landsat-8 images are 16 bit and thus rescaling of the bands to 8-bit as per the method followed in FCD model. No atmospheric correction was done on the bands. A water mask was obtained by running unsupervised classification to mask out the parts of the water from the images. All the selected mangrove sites were digitized with high imagery in ArcGIS. The water mask was applied for all sites.

The Landsat-8 was primarily chosen due to the input requirements of the FCD model and the spectral bands of the Landsat-8 could not be adapted to other high resolution imagery.

1. Measuring Forest canopy density A FCD model developed by Roy et al. (1996) was implemented as software called FCD mapper software. Since, software presented technical issues while running in modern operating systems, therefore a model was developed in ArcGIS. Figure 3.3 depict the workflow for implementing the FCD model using ArcGIS.

Masked bands of Landsat-8 were used for calculating the indices described below. The bands used in calculation indices as per given in table 3.1.

- (a) Advanced vegetation Index (AVI)

This vegetation index was calculated using power degree of infrared response (Roy et al., 1996). It reacts sensitively to forest density better than other vegetation index like NDVI. This is advantageous to clearly distinguish the canopy of the mangroves. AVI is calculated as:

$$AVI = [B5 (255 - B4) (B5 - B4)]^{\frac{1}{3}}$$

- (b) Shadow Index (SI)

The difference in the crown of the trees leads to shadow patterns that affect the spectral

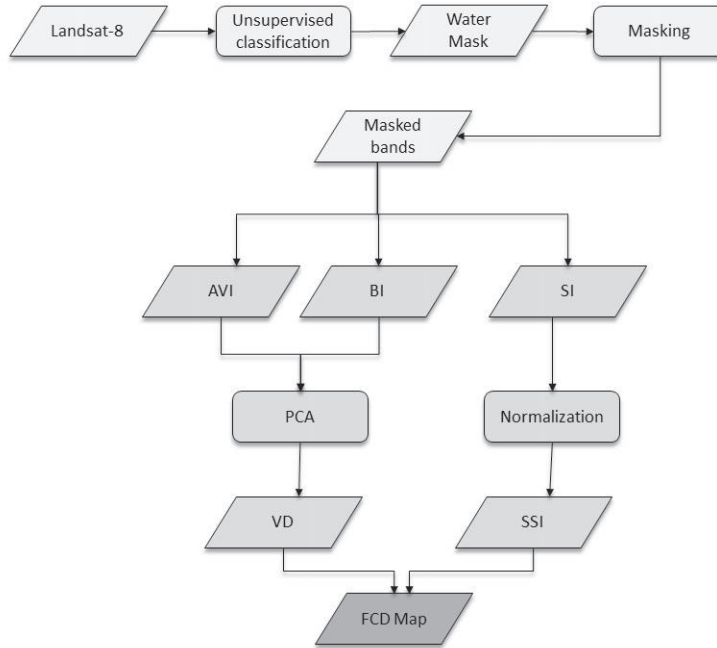


Figure 3.3: Workflow for calculating the Forest Canopy Density(FCD) in ArcGIS.

Table 3.1: List of Landsat-8 bands and their wavelength

Band	Wavelength	Resolution
B2 - Blue	0.450 - 0.515 $\mu\text{m}$	30 m
B3 - Green	0.525 - 0.600 $\mu\text{m}$	30 m
B4 - Red	0.630 - 0.680 $\mu\text{m}$	30 m
B5 - NIR	0.845 - 0.885 $\mu\text{m}$	30 m
B6 - SWIR	1.560 - 1.660 $\mu\text{m}$	30 m

response in calculation of vegetation. This index was developed to remove the effect of shadow while calculating the canopy density. SI was calculated as:

$$SI = [(255 - B2) (255 - B3) (255 - B4)]^{\frac{1}{3}}$$

(c) Bare Soil Index (BI)

Bare Soil Index is a normalized index of the difference of sums of the reflective and absorption bands of Landsat. It helps to separate vegetation from background areas. BI was calculated as:

$$BI = \frac{[(B6 + B4) - (B5 + B2)]}{[(B6 + B4) + (B5 + B2)]}$$

Scaled shadow index and Vegetation Density are thereafter calculated using the AVI, BI and SI.

Scaled Shadow index (SSI) SI is a relative value. Its normalized version was used to integrate its values with other indices. SSI was thus obtained by rescaling of SI to the scale of 0-100.

Vegetation Density (VD) synthesizes the AVI and BI by Principal Component's analysis. Later, rescaling of the value was done from 0 to 100 percent.

The final values for FCD was then obtained from the following formula.

$$FCD = (VD * SSI + 1)^{\frac{1}{2}} - 1$$

These values result into a map representing canopy density in percentage per pixel. This is the FCD map which is used in the next step for calculating the gaps. See figure 5.1.

2. Extracting point data The mangrove sites were delineated by digitizing these areas. Four individual FCD maps for every site were obtained using delineated area of the sites. A binary map of every site was then obtained by assigning a threshold over the value of canopy density from the FCD map. All the polygons representing degraded locations were then converted to points, with the centroids of the polygons. As a result, a set of points representing canopy gaps was obtained. Co-ordinates and area corresponding to every point was calculated. Another variable proximity to water was calculated using the water mask for every point in the pattern. This was done because based on site descriptions, it was noted that the main cause affecting mangroves is water pollution in the creeks.

The choice of threshold for value of canopy density was approximated by studying the overall minimum and maximum value of the canopy density. The thresholds from 50-54% were used for primary analysis to obtain 5 point patterns. The J function analysis, as described in section 4.3.1 for these five point patterns were analysed. Threshold of 52% for FCD was chosen and used to identify gaps for all sites. Refer Appendix B for the results for J function plot of point patterns.

In summary, this chapter introduces the mangrove sites, the data that will be used, selection of variable related to degradation and the means to measure them using canopy density. The points thus obtained is further used in statistical analysis by point pattern analysis. The main interest in analysis of the distribution of gaps is to investigate whether it can lead to any conclusions about the degradation process and ultimately about tipping point.



## Chapter 4

# Statistical method

Point pattern analysis is based on an assumption that the spatial patterns reflect the past processes and are like "ecological archives" from which the information about the process can be uncovered. However, doing so is challenging since the pattern is a result of highly complex and dynamic ecological processes. In conclusion, same patterns can be a result of different processes and causality might not be straightforward. This uncertainty in the analysis can be attributed to incomplete knowledge of the properties of the observed point patterns. Wiegand and Moloney (2013) thus suggests the use of pattern oriented modelling to integrate ecological theory and analysis of spatial pattern. This chapter presents the concept of J-function for point pattern analysis and Strauss model for fitting the model to the data. This is later followed by its implementation in R software.

### 4.1 GENERAL APPROACH FOR TIPPING POINT

Degradation in the mangroves is indicated by the canopy density, that is calculated using FCD model. The areas with low canopy density were classified as gaps and converted its centroids as points. A point pattern representing degradation was formulated for statistical analysis. By analysing the statistical properties of the spatial distribution of points and modelling the data with the covariates it is possible to identify any spatial trends in the point pattern leading to inference about tipping point. Figure 4.1 gives the overview of all the steps followed in the study described above and the following statistical analysis.

### 4.2 DEGRADATION AND INTERACTION IN THE POINT PATTERN

The level of degradation in mangroves indicates the type of interaction in the point pattern. The idea is to study degradation and interaction of the points in the point pattern and state a basic conceptual relation between the behaviour of gaps and type of interaction in the point pattern. Figure 4.2 shows a conceptual diagram of this proposed relation. A less or a highly degraded mangrove shows regular interaction in the point pattern. This is because both the conditions produce isolated gaps. They can be differentiated by the size of the gaps. A medium degraded mangrove represents clustered interaction between the points. This is because when the level of degradation increases, there is increase in the size of the gap or a new gap is formed. Hence, leading to formation of a new point or increase in size of the gap. Eventually, with increasing degradation leads to merging of points to each the level of highly degraded mangrove. Hence, this concept demonstrate the change in interaction with increase in level of degradation. Study of mangroves on these lines could lead to identification of tipping point by studying the interaction of points.

### 4.3 EXPLORATORY ANALYSIS OF POINT PATTERN

Statistical analysis of spatial patterns involves analysis of the data in three forms: quantitative data (continuously distributed in space), categorical data (like lattice data) and point pattern data (loca-

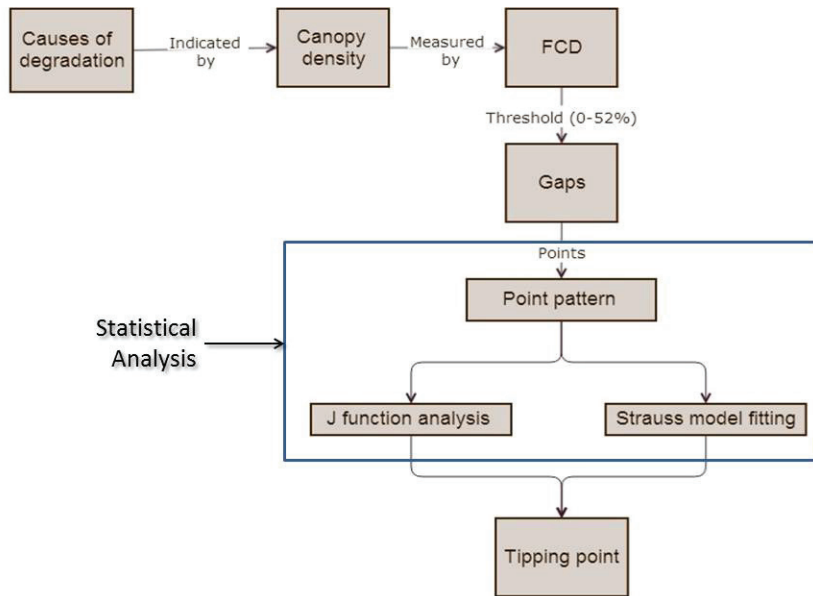


Figure 4.1: A general approach for statistical analysis for identifying tipping points in mangroves.

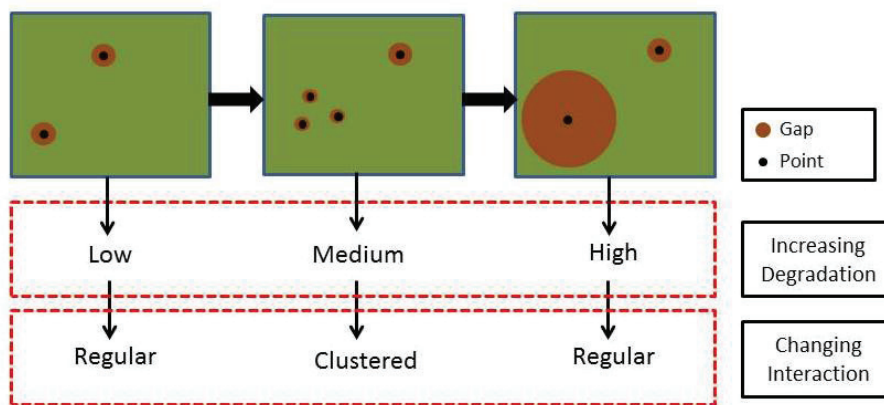


Figure 4.2: Relation between degradation level and point patterns.

tion in space). The main motive in exploratory analysis of those data forms is to assess the process behind the observed data. After compiling the data and information about the ecological process being studied, the first step is to determine appropriate data types and then decide whether the pattern is homogeneous or heterogeneous. The second step is to select an appropriate summary statistics to describes the properties of the spatial structure of the observed point pattern.

Planar point pattern is characterized by the locations of the points in geographic space. Marked point patterns have marks attributed to the points along with their locations. The choice of the type of pattern depends entirely on the data available. It is an important because the approach for both is different. For this study, both planar and marked point pattern were studied.

Homogeneous or heterogeneous property of the point processes are associated to the causes that led to its formation. Homogeneous process implies that the process or conditions responsible for the point to appear are same as all the points in the point pattern. On the other hand, heterogeneous process results due to varied environmental conditions in the observed space of the spatial point pattern. The assumption of the process being homogeneous or heterogeneous is a basic step in analysis of the point pattern. Because of the convenience of the property of the process being homogeneous, most of the studies assumed homogeneity for their study. The bias introduced as a result of this assumption may lead to misleading results. Nonetheless, it should also be noted that though ecological processes are heterogeneous, at a smaller scale of observation the condition for the resulting point processes may be a homogeneous process. This reason can play an important role in deciding the property of the process.

Summary statistics are metrics that characterizes data i.e the statistical properties of spatial point pattern (Illian et al., 2008). They are key to explore the spatial interaction structure. The choice of using the summary function depends entirely on the type of data and hypotheses that is being explored. Summary statistics is divided into different types: numerical or functional, and location or point related. They are commonly used for exploratory analysis. Ripley's K-function is the most widely used function. It is a functional point related summary statistic based on the mean number of points within interaction distance from a typical point.

Summary statistics can be further subdivided into first order and second order statistics(Diggle, 2003; Wiegand & Moloney, 2013). The first order properties are described by the mean number of points i.e intensity. This is usually measured by the concept of product density, which basically gives the configuration of points in space. First order product density characterizes the point density around a point  $x$ , is called an intensity function  $\lambda(x)$ . Second order statistics are dependent on spatial relationship between pairs of points in the pattern. Therefore, second order product density is described by the dependence on the location of points  $x_1$  and  $x_2$ .

#### 4.3.1 J function: A new summary statistic

Using the two distance based statistic F-function and G-function, a new measure of summary statistics called as J function was introduced by van Lieshout and Baddeley (1996). G-function is the empty space function which gives the distance between an arbitrary point and actual point, while F- function is a nearest neighbour function which gives the distance between two neighbouring points. It defines the range, strength and type of the interaction structure of the point pattern. It is sometimes useful to detect transition from the Poisson process and characterizing the interaction of points in the pattern. This function is described as

$$J(r) = \frac{1 - G(r)}{1 - F(r)} \quad (4.1)$$

The value of J function gives  $J(r)=1$  for Poisson process, any value greater than 1 suggest regularity and less than 1 suggests clustering. The estimate of J-function is significant in the sense that the

denominator will be small for large  $r$  and hence large fluctuations are more for these values of  $r$ .

J function for inhomogeneous process was proposed by van Lieshout (2011) by extending the effect of second order intensity re-weighted measure proposed by (Baddeley, Møller, & Waagepetersen, 2000). This measure is the weighted value for every point in the point pattern according to the estimated intensity at its location. To measure the J-function defined in equation 4.2, G function and F function was expressed in terms of product density. Later, for an intensity re-weighted moment stationary point process, van Lieshout (2011) J-function was defined as

$$J_{inhom}(t) = 1 + \sum_{n=1}^{\infty} \frac{(-\bar{\lambda})^n}{n!} J_n(t), \quad (4.2)$$

where,  $J_{inhom}$  converges to a finite value. In equation 4.2,

$$J_n(t) = \int_{B(0,t)} \dots \int_{B(0,t)} \xi_{n+1}(0, x_1, \dots, x_n) dx_1 \dots dx_n,$$

and  $\bar{\lambda}$  is the estimated intensity from the point pattern.  $\xi_n$  is the  $n$ -point correlation function over  $B(0,t)$ , which is area of radius  $t$ .

#### 4.3.2 Estimator of J-function

To estimate the value for the J-function, an estimator was defined by (van Lieshout, 2011). The nearest neighbour and empty space function is first defined in terms of generating functional. Generating functional uniquely describes the distribution of the point process in space (Daley & Vere-Jones, 2007). It is defined as

$$G(v) = \mathbb{E}\left[\prod_{x \in X} v(x)\right]$$

For all functions  $v = 1 - u$ ,  $u$  is function with bounded support. By convention, empty product is taken equal to 1.

From equation 4.2,  $J_{inhom}$  was defined by van Lieshout (2011), for  $t \geq 0$ ,  $a \in \mathbb{R}$ ,

$$u_t^a(x) = \frac{\bar{\lambda} 1\{x \in B(a, t)\}}{\lambda(x)} \quad (4.3)$$

as

$$J_{inhom}(t) = \frac{G^{1a}(1 - u_t^a)}{G(1 - u_t^0)} \quad (4.4)$$

where,  $G^{1a}$  is the generating functional at point  $a$  and denominator is non-zero.

Estimators of the J function was given in terms of generating functional. Consider a set  $W$  in which point pattern  $X$  is observed of intensity  $\lambda$ . An eroded set  $W_{\ominus t} = \{x \in W : x + B(0, t) \subseteq W\}$ . The estimator  $G(\widehat{1 - u_t^0})$  is defined with a finite point grid  $L \in \mathbb{W}$ , for all grid points  $l_k \in W_{\ominus t}$  as

$$G(\widehat{1 - u_t^0}) := \frac{\sum_{l_k \in L \cap W_{\ominus t}} \prod_{x \in X \cap B(l_k, t)} \left[1 - \frac{\bar{\lambda}}{\lambda(x)}\right]}{\#L \cap W_{\ominus t}} \quad (4.5)$$

and similarly,  $G^{1a}(\widehat{1 - u_t^a})$  is estimated fro  $x_k$  of  $X \cap W_{\ominus t}$  by,

$$G^{1a}(\widehat{1 - u_t^a}) = \frac{\sum_{x_k \in X \cap W_{\ominus t}} \prod_{x \in X \setminus \{x_k\} \cap B(x_k, t)} \left[1 - \frac{\bar{\lambda}}{\lambda(x)}\right]}{\#X \cap W_{\ominus t}} \quad (4.6)$$

#### 4.4 MODEL FITTING FOR COVARIATE

The effect of the covariates and spatial trends can be studied by fitting spatial point process to the point pattern. Point processes characterize stochastic mechanism of the underlying process. In this case, it is the degradation process. In analysis of the pattern as a result of degradation, properties related to the trend and covariate need to be explored.

The J-function shows the kind of interaction between the points. Hence, the dependence of the points may exist between neighbouring points in the pattern. This can be explained by assuming that the pattern of gaps exhibit Markov property and the point process is a Markov point process. This assumption with the effect of covariate can explain the causes related to the points.

Pair-wise interaction process was introduced for interactions within a fixed distance (Ripley, 1977). Strauss process is an example of this which also shows Markov property. Hence, Strauss process was studied to describe the interaction structure of the observed point pattern. Strauss model gives the probability density of a point pattern based on contribution of every point, and the distinct pair of points closer than an interaction radius  $r$ . It is given by Diggle (2003) as

$$f(x) = \alpha \beta^{n(x)} \gamma^{s(x)} \quad (4.7)$$

where  $n(x)$  is number of points,  $s(x)$  represents the distinct unordered pairs of points and  $\alpha$  is a normalising constant. A factor  $\beta$  is contributed by every point to the probability density while a factor  $\gamma$  is contributed by every pair of points closer than  $r$  units apart to the overall density given in equation 4.7.  $\gamma = 0$  is defined for hard core process, while  $0 < \gamma < 1$  exhibits inhibition between points. This model was originally described with  $\gamma > 1$ , but was later proved to be invalid. This was because the resulting pattern shows extreme form of clustering to form a single cluster of points. Refer (Diggle, 2003; Gates & Westcott, 1986) for more details.

Probability density function value is the most convenient way to describe a point process, but is difficult to grasp (Turner, 2009; Baddeley & Turner, 2006). Hence, 'Papangelou conditional intensity function' (Papangelou, 1974; van Lieshout, 2000) was described for easier understanding of the point process. This is conditional intensity function  $\lambda(u, x)$  of spatial location  $u \in W$  and the entire point pattern  $x$ , where  $u$  is the point observed in observation window  $W$ , and given by the formula

$$\lambda(u, x) = \frac{f(x \cup u)}{f(x)}$$

For pairwise interaction process, conditional intensity is given by

$$\lambda(u, x) = \beta \prod_{x_i \in W} h(u, x_i)$$

where  $h(u, x_i)$  represents the parameter  $\gamma$  in equation 4.7.

#### 4.5 IMPLEMENTATION

The analysis of the point pattern was done in R using Spatstat package by Baddeley and Turner (2005). Spatstat was specifically developed for analysis of the spatial point patterns. The point patterns obtained for the four mangrove sites were put into R. The area of the respective sites was taken as the observation window for the analysis. The selection of observation window was essential for analysis because it affected the intensity of the point pattern. This process was implemented for all the mangrove sites.

#### 4.5.1 J-function analysis

The point processes are heterogeneous in nature like the ecological processes. The process of degradation is a complex ecological process in which various causes may result into similar point pattern. The current point pattern is a result of different causes which could not be differentiated in this study. Further analysis with J function was done by considering degradation of mangroves as heterogeneous process.

Using spatstat package in R, J function is implemented for an inhomogeneous process. For inhomogeneous process, the intensity is a function of every point in the point pattern. Intensity is the number of gaps per unit meter. This is different for all points in this inhomogeneous point process. The kernel density estimate represents the variation in the intensity of the point process. This estimate is computed by fixed bandwidth kernel. The bandwidth of the kernel is computed from the cross validated kernel selection method (Diggle, 1985). This bandwidth computation is done from the existing point pattern.

The J-function is a distance based summary function. This function is implemented in R with the estimator defined in Equation 4.5 and 4.6 (Baddeley & Turner, 2005). This J function value is calculated for all the four point patterns of the mangrove sites. The result from applying J-function for heterogeneous process are explained in Chapter 5.

#### 4.5.2 Strauss model

Strauss model was used to fit to the point pattern. This was implemented for Site 1. Modelling with covariates was done using the ppm function in Spatstat package in R. This function fits the selected model to the observed data for the given trend. The trend was a function of the X coordinate, Y coordinate and covariate. The calculated distance to water was taken as a covariate. The selection of this covariate was because, the water pollution was the main cause affecting the mangroves at all sites.

A quadrature scheme is required to model the effect of covariate in R. The quadrature schema includes dummy points apart from the observed points. Hence, equal number of dummy points were generated to match the number of points in the original dataset. It uses Berman-Turner approximation to compute the fit (Baddeley & Turner, 2006).

The implementation of Strauss model requires a fixed irregular parameter, interaction radius  $r$  as input. The result of predictions was based on the model giving conditional intensity at the location of the point with effect of covariate. The predict function gives the conditional intensity of the point process. Weighted density estimate was plotted with the conditional intensity as the weights. The values from predict function computed the conditional intensity at the location of points in the pattern in Spatstat. Seven simulated realizations for range of values  $r$  was obtained through this process. The results that were obtained are as shown in 5.

In this chapter, the conceptual relation between degradation process and interaction of points was proposed. The type of interaction was studied with the J-function and the point pattern for four mangrove sites. The study of spatial distribution of degradation, was done with the point pattern and the covariate explaining the causality for the process.

## Chapter 5

# Results

The results of the implementation about point pattern, J function and the Strauss model is given in this Chapter. The results of measurement of variables is shown in Section 5.1. The results of the summary statistics for the observed point pattern using J-function is described in Section 5.2. The Strauss model was fitted to the point pattern for one of the mangrove sites with the explanatory variable proximity to water. The results are described in Section 5.3.

### 5.1 RESULTS FROM MEASUREMENT OF VARIABLE

Point pattern, area of the degraded parts of mangroves and proximity of every point to water are the final variables that were calculated. Figure 5.1 shows map of the FCD values with all the four mangrove sites. Visually, low density can be identified at all the selected sites. The range of value for forest canopy density lies between 0 - 76% for the complete scene. So, when individual FCD map for all 4 mangrove sites was derived, the values shown in 5.1 were obtained. This distinction shows the range of canopy density at every mangrove site. The ranges for each site are not equal. The minimum values fro all four sites vary between 30 and 40%.

Table 5.1: The range of Forest Canopy Density(FCD) values for the four mangrove sites

Site	FCD range(%)
Site 1	30-64
Site 2	32-62
Site 3	40-63
Site 4	37-66

A binary map was obtained with a fixed threshold of 0-52% to classify degraded and non-degraded areas. Figure 5.2(a) shows the binary map for site 2. The resulting polygons varied in size and depended on the extent of degradation of the mangrove sites. All the polygons that were derived in this process were assumed to be degraded areas and centroids were calculated and designated as gaps, as shown in figure 5.2(b) for site 2.

After implementing the same process for all four sites, the point patterns as shown in Figure 5.3 were obtained. The point pattern for site 1 have localised clusters of points at certain locations. The point pattern of site 2 have fewer points and mainly at the edges along the land boundary for the complete site. The point pattern at site 3 and site 4 show similar patterns of many points lying along the boundaries of water.

In order to study the effect of the size of the gaps, area of the gaps were calculated for the degraded polygons. Table 5.2 gives a summary of the variable area, for the four mangrove sites. It shows that site 2 has the least number of points compared to other sites. The minimum area for all sites is almost similar, while the maximum area varies widely, with Site 3 and Site 4 having very

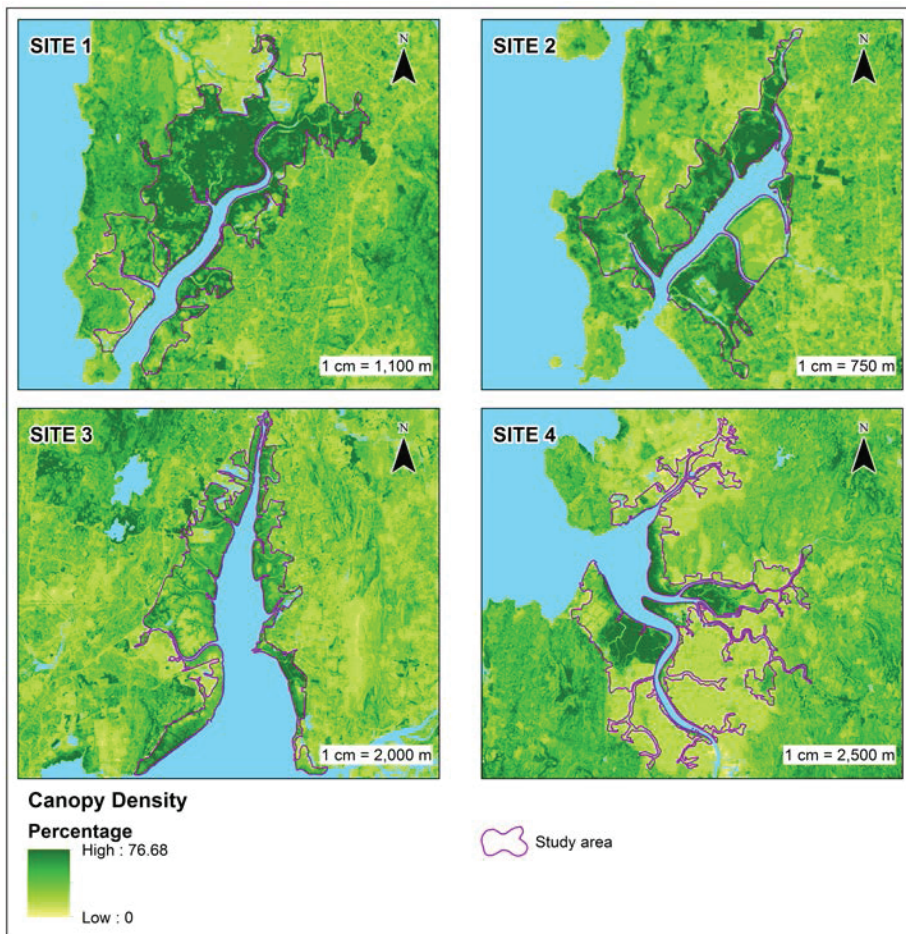


Figure 5.1: Final FCD Map for four sites as described in section 1.

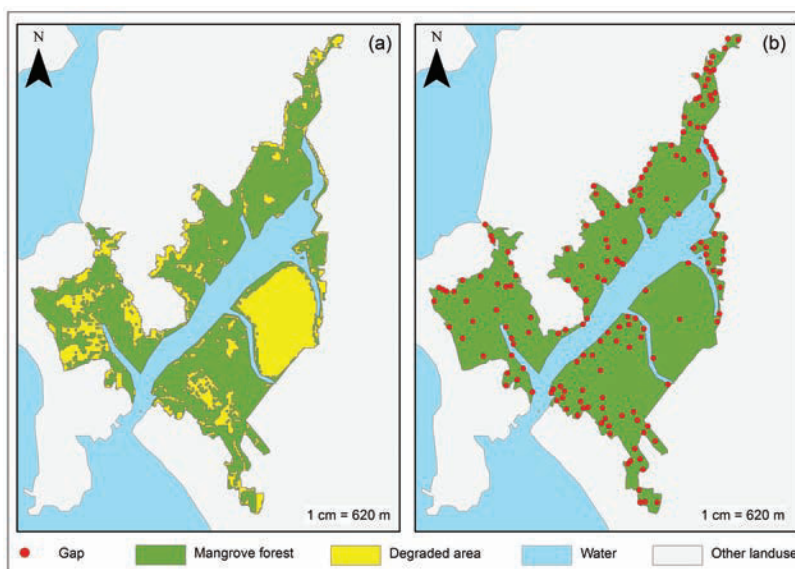


Figure 5.2: Degraded areas as polygons and gap centroids at site 2.

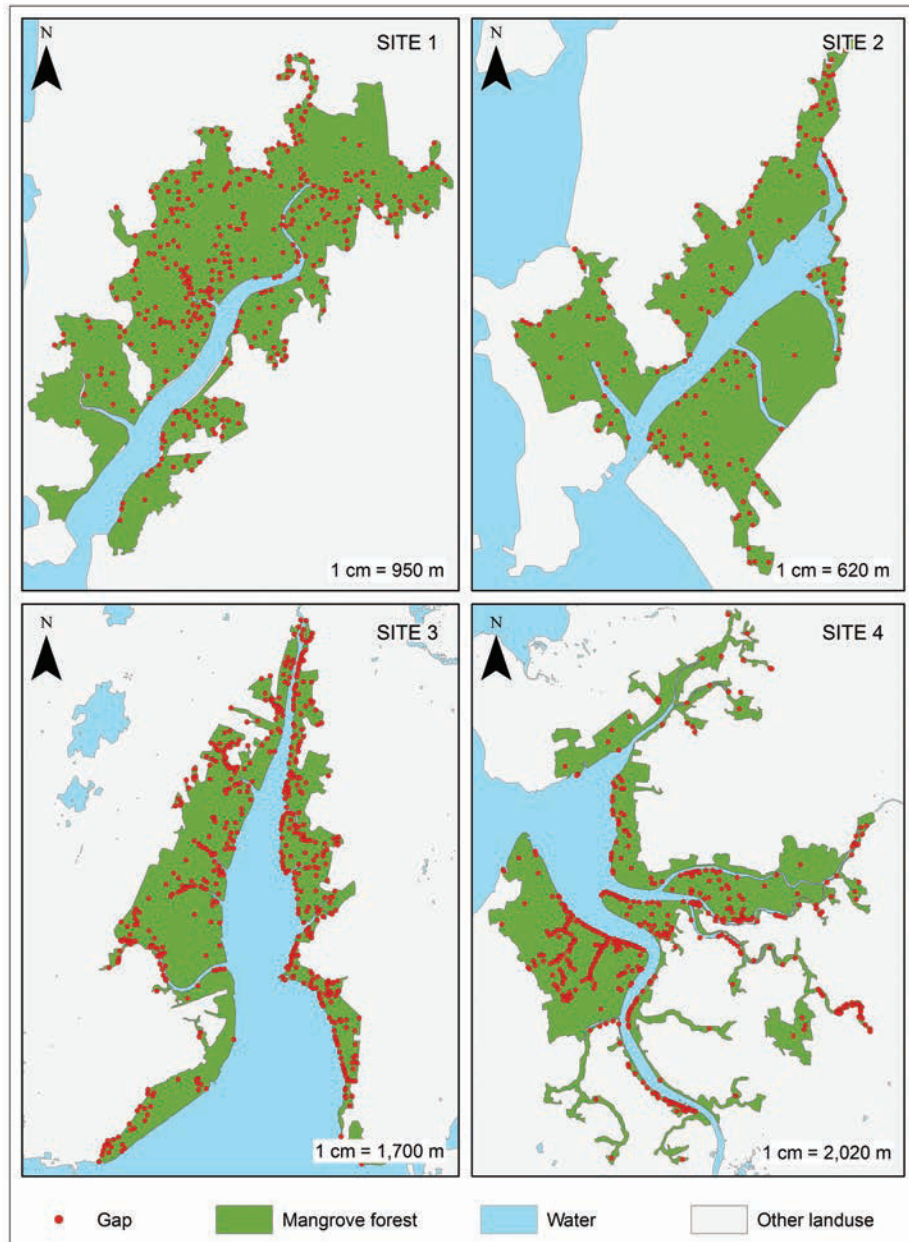


Figure 5.3: Resulting point pattern for all the four sites.

large maximum areas and showing bigger degraded gaps in these sites. Comparatively, the mean and standard deviation is higher for site 4.

Table 5.2: Summary of the calculated area of all the polygons for the four mangrove sites

Site	Count	Area(ha)	Min(ha)	Max(ha)	Mean(ha)	Std.dev(ha)
Site 1	353	2900	0.11	247.17	2.8	18.44
Site 2	170	1000	0.18	141.75	2.05	11.19
Site 3	502	5600	0.18	617.94	5.58	36.03
Site 4	448	8900	0.18	749.07	12.6	69.12

## 5.2 RESULT FROM EXPLORATORY ANALYSIS OF POINT PATTERN

The intensity of the point pattern was calculated for all four sites. Table 5.3 shows the values for intensity of points per square metre for the four sites. The value of average intensity is comparatively low for all the sites, but much lower for sites 3 and 4 than for sites 1 and 2. This is likely due to the fact that sites 3 and 4 are much bigger than sites 1 and 2 (as can be seen in table 5.2).

Table 5.3: Average intensity of points for four mangrove sites

Site	Avg intensity(per m <sup>2</sup> )
Site 1	$1.2 \times 10^{-4}$
Site 2	$1.7 \times 10^{-4}$
Site 3	$8.6 \times 10^{-6}$
Site 4	$5 \times 10^{-6}$

To show the effect of the area, the kernel density was estimated with the area of the corresponding gaps as weights. Figure 5.4 shows the result for density estimate with gaps as black dots. It shows that the points with high value of areas bias the estimate by giving higher value of intensity at those respective points only, which hides all the smaller gaps. This is visibly marked in the Figure 5.4.

The J-function gives description about the type and strength of interaction in the point pattern. Figure 5.5 shows the result from the J function of the point pattern obtained for site 1 and the corresponding estimated kernel density for the pattern. It was observed that the value of  $J(r)$  was equal to 1, representing a random pattern. Also, fluctuations in this value are observed at varying interaction radius  $r$ . The kernel estimate for this site has values between 0 and  $5 \times 10^{-6}$ . It shows high intensity values around the central part of the study area.

Figure 5.6 shows the plot for the J-function for site 2. An exponential curve with minimum fluctuations was observed in this plot. The value for the J-function is greater than 1 to 1.4 for increasing interaction radius  $r$  of 400m, therefore indicating strong regularity in the pattern. The kernel density estimate has overall value of 0 to  $1.2 \times 10^{-4}$ . It shows minimum intensity around the entire study area except along the boundaries of the point pattern.

Figure 5.7 shows the J-function plot and kernel density estimate for site 3. This graph shows a different trend in the value for J-function with values varying between 1 and 1.001 until interaction radius  $r$  of 600m. Thus indicating alternate regularity and randomness in the point pattern and a

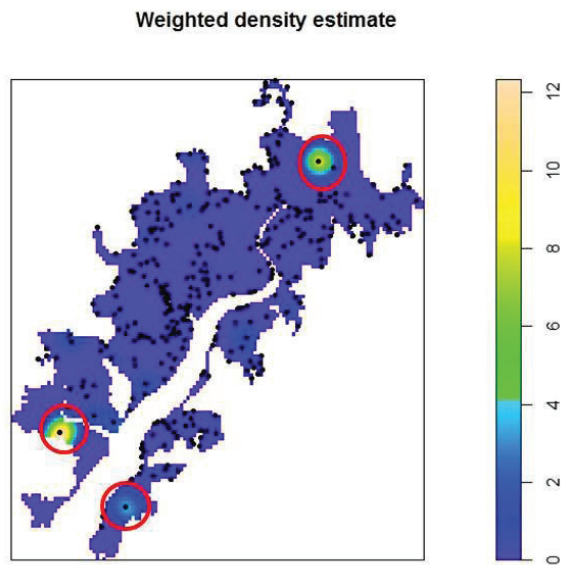


Figure 5.4: Density estimate with area as the weight for the point pattern of site 1.

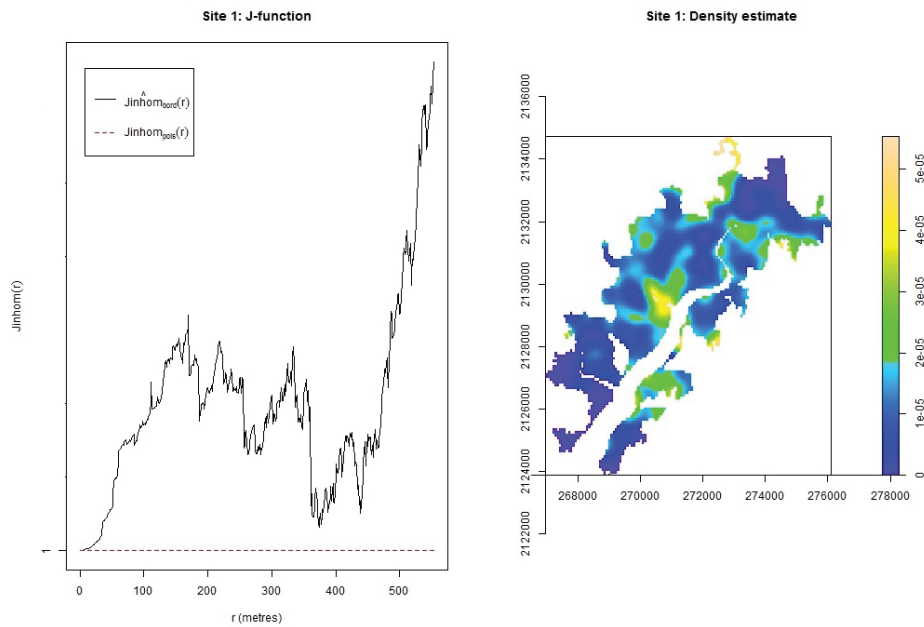


Figure 5.5: J-function plot and density estimate for site 1.

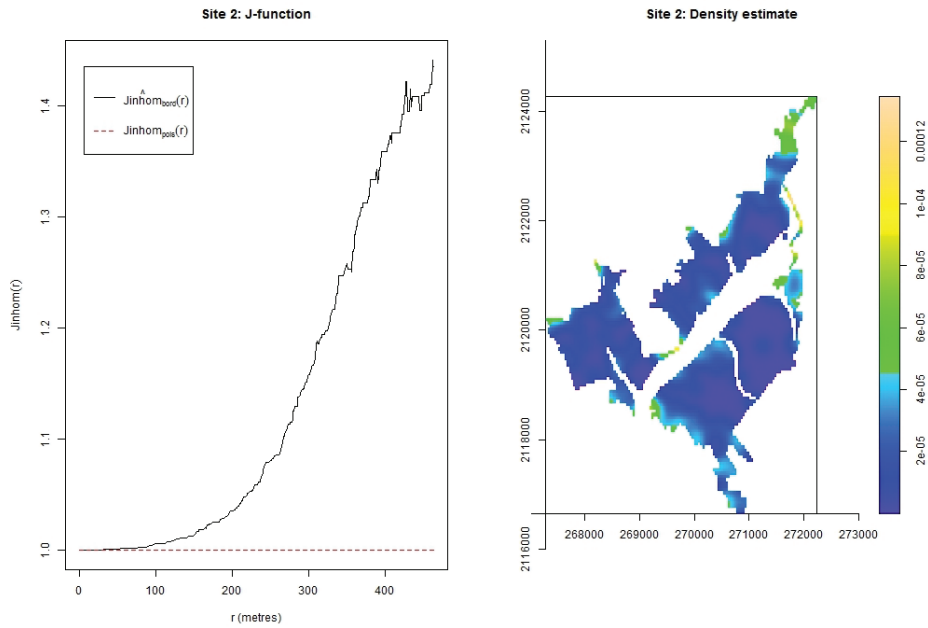


Figure 5.6: J-function plot and density estimate for site 2.

very weak strength of interaction. The kernel estimate is also low for this site except where the observation window is narrower.

Figure 5.8 shows the J-function and density estimate for site 4. The value of the J-function is greater than 1 implying regularity in the pattern. Although, the strength of this interaction is weak due to lower value of  $J(r)$  of 1.08. The graph of this plot shows fluctuations for higher interaction radius between 600m - 800m. However, the kernel estimate for this site is very low except at few parts with values between  $3 \times 10^{-5}$  and  $8 \times 10^{-5}$ .

### 5.3 RESULTS FROM MODEL FITTING

The Strauss model was fitted to the point pattern including the covariate for site 1. Section 4.4 described the Strauss model and 4.5.2 explained its implementation in R. Table 5.4 gives the values of the interaction coefficient and the parameter  $\gamma$  from fitting the model for values of  $r$ . It shows increasing value for  $\gamma$  as the interaction radius is increased from 100m to 400m after which it decreases for 700m. For  $\gamma < 1$  this model describes ordered pattern while  $\gamma > 1$  are values of radius which are not valid, likely because the pattern is clustered. We observe regular pattern for less than 100m and beyond 700m and clustering between 200-600 m for the point pattern.

The values for the predicted conditional intensity were calculated for all the locations of the point pattern from the probability density of model fitting. Weighted kernel density estimate with this conditional intensity was plotted as shown in figure 5.9. It shows seven realizations for varying interaction radius  $r$ . The model shows the high density at the centre of the study area for all realizations except when the interaction radius is 500m and 700m. In addition, for all the estimates it was observed that in the north-east and south-west parts of the study area shows very low intensity. Overall the spatial extent of the interaction area decreases for increasing distance  $r$ .

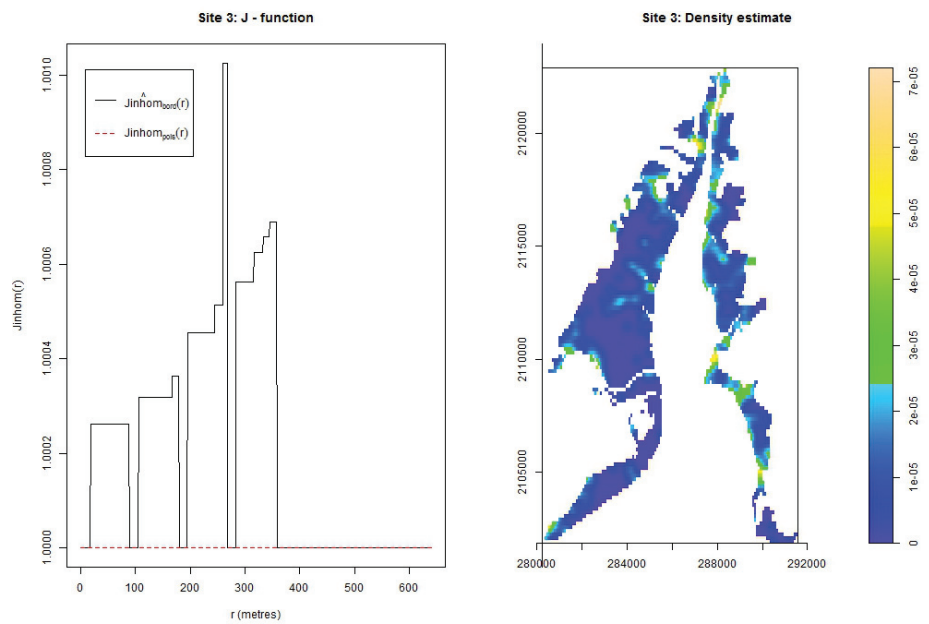


Figure 5.7: J-function plot and density estimate for site 3.

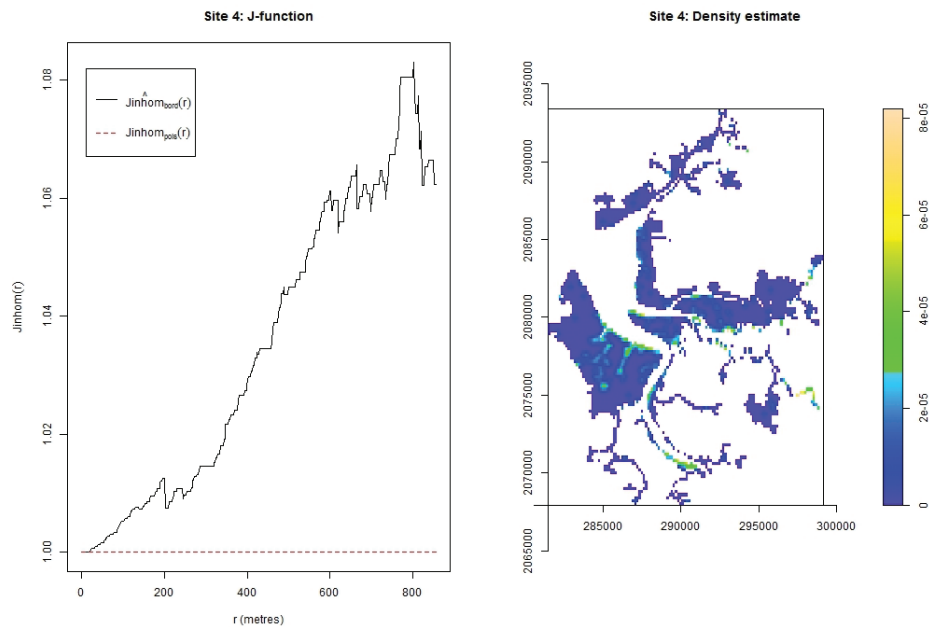


Figure 5.8: J-function plot and density estimate for site 4.

Table 5.4: Results from the Strauss model fitting for site 1

$r(m)$	Interaction coefficient	$\gamma$
100	-0.455	0.635
200	0.241	1.272
300	0.181	1.198
400	0.197	1.218
500	0.106	1.112
600	0.046	1.048
700	-0.193	0.825

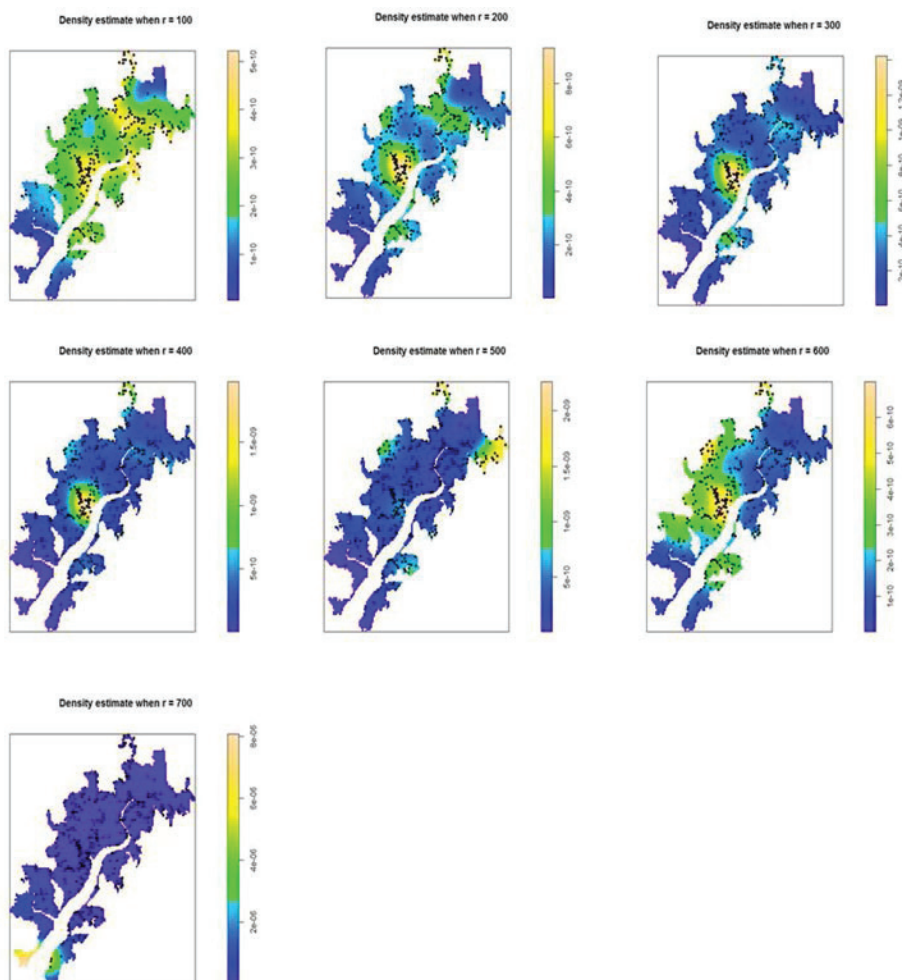


Figure 5.9: Results of the Strauss model with the observed point pattern

## Chapter 6

# Discussion

The causes of degradation of mangroves vary from site to site. The canopy structure was identified as indicator of state of mangroves and hence for degradation status of mangroves. Canopy density was the variable associated to measure this form of structure; low canopy density areas were identified as gaps in canopy. For statistical analysis, these gaps were converted to points. Other variables like size of the gaps and distance to water was calculated for all the points. These points were converted to point pattern. The following sections discuss the results of the variables and statistical analysis for the four selected mangrove sites.

### 6.1 DISCUSSION ON VARIABLES RELATED TO DEGRADATION

According to figure 3.2, the measurable variables for degradation were the number of gaps and size of gaps. Accordingly, these gaps were measured as points and area of gap respectively, using the forest canopy density model. Refer appendix A for the maps of four site with the individual FCD map, the degraded polygons and resulting point pattern. The choice of threshold of was based on the J-function of the five point patterns. Some interaction was noted for the point pattern with threshold of 52 and 53. With threshold of 52, all the pixels with canopy density value less than 52% were assumed to be degraded. This assumption of the choice of threshold is limitation of this study and uncertainty introduced by this limitation affects the location of points and the area of the gap.

Visual interpretation of the point pattern that was obtained after taking into consideration four sites, showing that the points were located along the edges of water except for site 2 where more points were located along the boundaries with the land. Therefore, the site 2 is more affected by the causes from the land and others due to the water. Field information is required to confirm this reasoning.

The summary of the other variable area was given in 5.2. This shows that the range of values for the area is extremely large. Hence, the point pattern consists of extremely large and small gaps. However, the low mean and standard deviation indicates that very few big size gap exists. This was observed when density estimate of the point pattern was calculated with area as the weight as seen in figure 5.4. These points produced biased result for analysis.

### 6.2 DISCUSSION ON EXPLORATORY ANALYSIS OF POINT PATTERN

#### 6.2.1 J-function

The point pattern analysis was performed with assumption of heterogeneous point process. The use of inhomogeneous J-function for analysis reduced the bias that would be introduced in the point pattern due to environmental conditions. In case of assumption of homogeneity, all the points would be a result of only one cause. This is not right because the summary of the area of the degraded gaps show that extreme small and big gaps are formed. On visual interpretation of such big size polygon showed these gaps were due to presence of salt pans and clearing of a large

part of the site for urban expansion. This reasoning is similar for other sites as well. Hence, the degradation process is heterogeneous for all the mangrove sites in the study.

The types of interaction depicted by J-function is regular, random or clustered. In case of site 1, the plot of estimated  $J_{inhom_{bord}}(r)$  does not follow  $J_{inhom_{pois}}(r)$  for increasing interaction radius  $r$ . The estimated value of J- function is  $\approx 1$ , implying extremely weak regular interaction for the point pattern. Fluctuations in the plot are result of local clusters of points in the study area as observed in the density estimate in 5.5.

For site 2, the J-function showed strong regularity in the point pattern since the value for J-function was up to 1.4 for interaction range of 400m. This exponential increase in the plot indicates either no degradation or total degradation. Comparing the J-function results and area of degraded polygons, we observe that the parts with high and low level of degradation are present (Refer 5.2) on the east bank of this site. The J-function shows regular patterns an interaction radius around this region of the site. This confirms to the conceptual idea explained in Chapter 4 about level of degradation and type of interaction. And according to this theory, this is a highly degraded site, which confirms the site description mentioned earlier. Slight fluctuations in the plot for higher value of  $r$  was observed due density estimate value around the edges of the site.

Site 3 showed alternating trend in the plot for value of J-function as a random and regular type of interaction. This result is due to the narrow shape and the higher bandwidth of the kernel at those areas. This affects the estimated intensity of the points. The alternate possibility is that the point pattern that was obtained does not match the actual degradation process assumed. The type of mangrove in this specific site is a wetland with a mix of mangrove forests and mud flats, which may have emerged naturally (despite having very low canopy density). Mud flats offer most suitable conditions for new mangroves to grow. It comprises of a large part of wet marsh and young seedlings and trees. In this case, the canopy density is expected to be low. In addition, the spatial resolution of the Landsat-8 cannot clearly identify mangroves in such regions. Hence, the combined effect of the spatial resolution and young mangroves affected the correct identification of canopy density. This points to a limitation of the analysis method, specifically in the definition of the gaps by use of the FCD model.

The plot of J-function at Site 4 showed exponential increase without fluctuations representing either a low or high degradation. The FCD map of Site 4 comprises of mangroves around the central part of study area while the rest of the site showed very low canopy density. Refer map fro site 4 in appendix A. Thus, the J-function indicating regular pattern for low degraded mangroves. The indication of more fluctuations for distances greater than 600m represents clustering for this distance. This is also because the observation window for this site shows extremely narrow boundaries around this distance.

On the whole, the J-function indicated the type of interaction for degradation process only based on locations of the points, as described in the conceptual idea in Chapter 4. Even though the discussion of J-function indicates the validity of this model, proper validation with areas of those level of degradation is needed. When the gap size for degraded area was large, similar values for  $J(r)$  were obtained as the parts with no degradation. In other words, completely degraded areas result in similar  $J(r)$  values as the areas completely covered by mangroves. To differentiate between them, a marked point process would have been necessary to be more conclusive in the relation of interaction of points with the degradation process completely.

An attempt was made to analyse the point pattern of site 1 as a marked point pattern, with the area defining the mark. Multi-type marked point pattern was used for categorical variable with the assumption of the process being homogeneous. Hence, the point pattern was split based on the continuous variable of area into two types, i.e., 'Big' and 'Small'. Three points were classified as 'Big' category while the rest 350 for the other category. It was observed that no distinct interaction

between the two categories of the variable can be known. This can be attributed to two reasons: assumption of the process being homogeneous and the number of 'Big' gaps being very low, compared to the number of 'Small' gaps. This introduces a bias, since there are not enough points in one category for a proper analysis. Although the limitation was not decisive for the current point pattern, it may be necessary to apply this method to other patterns with significant number of points or another method for analysis.

The density estimate is the intensity function of the point process with a fixed bandwidth calculated by Diggle (1985). The variance in density estimate shows that the degradation process is heterogeneous for all four sites. Different causes lead to different points in the pattern. The density estimate for all four sites showed higher values where the intensity of points was higher. Clusters of small sized gaps showed high density, representing more degradation process around these regions. The isolated points having large and small value for area showed low density value. The density estimate was only partially related to the overall degradation process with the smaller gaps. It does not identify the larger gaps properly, resulting in a low density as the areas covered by mangroves.

Except for site 1, other sites had relatively lower density estimates. High density value was estimated for localised clusters in the site 1. Site 2, site 3 and site 4 showed high density only along narrower parts of the observation window, which are the only parts were a pattern of small gaps dominated. One of the reasons is that, these areas have been affected by different causes of degradation over a period of time and in present condition shows a narrow parts of mangrove. However, it is also known that mangrove lies along the coasts and do not spread more than 1km away from the water. More information from the field is necessary in such conditions to avoid misleading interpretations.

The possibility of degradation along the borders due to encroachment by the people, raises the issue of the choice of observation window. For the current study, present day mangroves borders were delineated. Hence, the mangroves lost in due time along the borders are not taken into consideration. Hence, on using a actual mangrove area from past years for observation window, could lead to increase in size of gaps around this regions. Hence, this will be useful for implementing marked point processes.

### 6.2.2 Strauss Model

Table 5.4 showed different values for interaction parameter  $\gamma$  for respective interaction radius. The values of  $\gamma$  for interaction radius  $r$  for 200-600m was greater than 1. The results of Strauss model in R, is not valid for values of  $\gamma$  greater than 1. Hence, only the results for  $r = 100m$  and  $r = 700m$  were valid and they implied regular interaction of points. In other cases (if  $\gamma$  is greater than 1), use of Geyer model is suggested (Turner, 2009). Therefore, modification is needed to fit Geyer model to the observed point pattern. This, however, was beyond the scope and resources of this research.

Although, not all results are valid because of the value of  $\gamma$ , no validation was yet performed to confirm the results of the fit. This needs to be done before modifying the Strauss model. The choice of the irregular parameter  $r$ , which is the interaction radius, can still be adjusted to obtain a proper and valid result; this aspect was not explored. The interaction radius is important because every other point within a distance  $r$  adds a factor value in the probability density of the entire point pattern. In essence, it is possible that the estimated Strauss model is valid if the proper selection of  $r$  lies within the valid ranges; until this  $r$  is appropriately selected and justified, one cannot discard the Strauss model. However, this process is not trivial and, because of its complexity, could not be completed within this project.

Assuming the Strauss process to be valid, conditional intensity was predicted at the point pattern locations. Using a kernel density estimate for these points, with conditional intensity as the

weight, a visualization of the pattern for the entire site was generated. The estimated density plots shown in figure 5.9 is with weighted intensity of points. As the interaction radius increases, the spatial variation of estimated density changes drastically. High density is observed at the centre of the site except when  $r = 500m$  and  $r = 700m$ , which might be attributed to division in the observation window. This area is the region of high interaction due to the local cluster and adjacent part of the water. It is likely that this is the region most affected due to water pollution at this site. It is noted that the points with big degraded area showed no interaction throughout the range of interaction radius. All areas for which the kernel density show similar ranges, can be assumed to be affected by the same cause of degradation. This, however, is not true for the bigger gaps because their estimated values are similarly low to areas completely covered by mangrove canopy.

From the results of the Strauss model, it is known that modifications to this method of model fitting is required. This has to be done by validating the fitted trend to the data and the selection of a justified interaction radius  $r$ .

### 6.3 DISCUSSION FOR TIPPING POINT

The observed point pattern is a representation of the effect of the degradation process. Point pattern analysis was implemented to establish association between inter-point interaction to model the underlying process of degradation at site level. A conceptual model was proposed in Chapter 4.

Tipping point represents a point of change in the state. For finding tipping point, proper states before and after have to be defined. And then, deviations between these states is where the tipping point lies and have to be looked for. Tipping point for degradation of mangroves is defined as a threshold after which the degraded mangroves forest cannot recover. Hence, the three states will be for pristine mangroves, partially degraded mangrove and completely degraded mangroves.

The result of J-function proved that interaction of points can be related to degradation process. It was observed that all the sites in this study have been in different levels of degradation. Some may be near tipping point or past the tipping point. Since the final state was not known, this could not be proved conclusively but strong indications do exist. Further study in the interaction type and strength for the first pristine and degraded mangroves would lead in the direction to identify tipping point.

A pairwise interaction model, the Strauss model for degradation of mangroves, was formed as a causal model demonstrating the effect of explanatory variable on degradation. This causal model describes the inter point interaction structure. Such a model is only capable of explaining the effects of individual causes of degradation in the mangroves forests. Hence, the J-function can be used to identify tipping point while the model fitting can be used to identify the spatial distribution of causes of degradation in the mangrove.

## Chapter 7

# Conclusion and Recommendation

The aim of this research was to integrate the concept of tipping point with degradation of mangrove forests using statistical methods and remote sensing techniques.

### 7.1 CONCLUSION

- Degradation is a result of mainly two causes in the case of mangrove forests around Mumbai. It is a cumulative effect of factors such as: intense urban pressure leading to change in natural cycle of forest regeneration, and water pollution by domestic and industrial waste. The effects of these causes are visible through variability in the canopy cover of the mangrove forest. This study illustrated the possibility of using canopy density as a measure to reflect degradation. The Forest Canopy Density model made possible to measure canopy density through the use of remote sensing techniques. The measurement of canopy density led to classification of low canopy density areas as degraded areas and gaps.
- Spatial distribution of points representing gaps were incorporated into a statistical analysis. Additionally, the size of the degraded areas and the proximity to water were considered as dependable and explanatory variables. Second order summary statistic, J-function was able to measure interaction for the point patterns.
- Results of the J-function at four sites showed that interaction between the points can be used for representing degradation.
- The relation of degradation of mangrove forest and interaction between the points indicates a possibility for finding tipping point. A relation of the behaviour of J-function for pristine and totally degraded mangrove is essential.
- The spatial variation of degradation process can be known by fitting a right model to the observed point pattern, and develop it into a causal model for degradation. The Strauss model showed the effect of an explanatory variable for fixed interaction radius. However, modification to this model is further required.

### 7.2 RECOMMENDATIONS

- Use of a higher spatial resolution for measuring canopy density, and validation of threshold value to classify degraded and non-degraded areas may lead to an improvement in description of degradation in mangroves through remote sensing.
- In statistical analysis, marked J-function is suggested to include the effect of size of the gaps as part of the degradation process.

- For fitting the model to the data, a justified value of interaction radius for Strauss model should be identified. Alternatively, Turner (2009) suggested the use of Geyer process for clustered interaction.
- For identify tipping point comparison of the J-function results for a pristine and completely degraded mangroves and this research can be done.
- Variables related to regeneration capacity of mangroves should be included in the study.
- Object oriented analysis of mangrove mapping with high resolution imagery can be used to identify canopy gaps(Kamal et al., 2014).
- Mangroves have a complex degeneration, regeneration and survival mechanisms running over a very long period of time. Spatio-temporal analysis may result in better understanding for identification of tipping point through statistical analysis.

## References

- Baddeley, A. J., Møller, J., & Waagepetersen, R. (2000). Non- and semi-parametric estimation of interaction in inhomogeneous point patterns. *Statistica Neerlandica*, 54(3), 329–350.
- Baddeley, A. J., & Turner, R. (2005). spatstat: An R package for analyzing spatial point patterns. *Journal of Statistical Software*, 12(6), 1–42.
- Baddeley, A. J., & Turner, R. (2006). Modelling spatial point patterns in R. In *Case studies in spatial point process modeling* (pp. 23–74). Springer.
- Blasco, F., Aizpuru, M., & Din Ndongo, D. (2005). Mangroves, remote sensing. In M. Schwartz (Ed.), *Encyclopedia of coastal science* (p. 614-618). Springer Netherlands.
- Boulton, C. A., Good, P., & Lenton, T. M. (2013). Early warning signals of simulated amazon rainforest dieback. *Theoretical Ecology*, 6(3), 373–384.
- Carpenter, S., & Brock, W. (2006). Rising variance: a leading indicator of ecological transition. *Ecology letters*, 9(3), 311-318.
- Carstensen, J., & Weydmann, A. (2012). Tipping points in the arctic: Eyeballing or statistical significance? *AMBIO*, 41(1), 34-43.
- Dakos, V., Scheffer, M., van Nes, E. H., Brovkin, V., Petoukhov, V., & Held, H. (2008). Slowing down as an early warning signal for abrupt climate change. *Proceedings of the National Academy of Sciences*, 105(38), 14308-14312.
- Dakos, V., van Nes, E. H., Donangelo, R., Fort, H., & Scheffer, M. (2010). Spatial correlation as leading indicator of catastrophic shifts. *Theoretical Ecology*, 3(3), 163-174.
- Daley, D. J., & Vere-Jones, D. (2007). *An introduction to the theory of point processes: volume ii: general theory and structure* (Vol. 2). Springer.
- DasGupta, R., & Shaw, R. (2013). Changing perspectives of mangrove management in india – an analytical overview. *Ocean and Coastal Management*, 80(0), 107 - 118.
- Diggle, P. (1985). A kernel method for smoothing point process data. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, 34(2), pp. 138-147.
- Diggle, P. (2003). *Statistical analysis of spatial point patterns* (Second edition ed.). London etc.: Oxford University Press (OUP).
- Drake, J. M., & Griffen, B. D. (2010). Early warning signals of extinction in deteriorating environments. *Nature*, 467(7314), 456-459.
- Duke, N. (2001). Gap creation and regenerative processes driving diversity and structure of mangrove ecosystems. *Wetlands Ecology and Management*, 9(3), 267-279. doi: 10.1023/A:1011121109886
- Fernandes, L., Nayak, G., Ilangovan, D., & Borole, D. (2011). Accumulation of sediment, organic matter and trace metals with space and time, in a creek along mumbai coast, india. *Estuarine, Coastal and Shelf Science*, 91(3), 388 - 399.
- FSI. (2011). *State of forest report 2011* (TECHREPORT). Forest Survey of India.
- Gates, D. J., & Westcott, M. (1986). Clustering estimates for spatial point distributions with unstable potentials. *Annals of the Institute of Statistical Mathematics*, 38(1), 123–135.
- Gladwell, M. (2006). *The tipping point: How little things can make a big difference*. Hachette Digital, Inc.

- Green, E. P., Clark, C. D., Mumby, P. J., Edwards, A. J., & Ellis, A. (1998). Remote sensing techniques for mangrove mapping. *International Journal of Remote Sensing*, 19(5), 935–956.
- Guns, R., Lioma, C., & Larsen, B. (2012). The tipping point: F-score as a function of the number of retrieved items. *Information Processing and Management*, 48(6), 1171 - 1180.
- Guttal, V., & Jayaprakash, C. (2008). Changing skewness: an early warning signal of regime shifts in ecosystems. *Ecology letters*, 11(5), 450-460.
- Illian, J., Penttinen, A., Stoyan, H., & Stoyan, D. (2008). *Statistical analysis and modelling of spatial point patterns* (Vol. 70). John Wiley & Sons.
- Kamal, M., Phinn, S., & Johansen, K. (2014). Characterizing the spatial structure of mangrove features for optimizing image-based mangrove mapping. *Remote Sensing*, 6(2), 984–1006.
- Kathiresan, K. (2002). Why are mangroves degrading? *CURRENT SCIENCE-BANGALORE*, 83(10), 1246–1248.
- Kathiresan, K., & Bingham, B. (2001). Biology of mangroves and mangrove ecosystems. In (Vol. 40, p. 81 - 251). Academic Press.
- Kéfi, S., Rietkerk, M., Alados, C. L., Pueyo, Y., Papanastasis, V. P., ElAich, A., & De Ruiter, P. C. (2007). Spatial vegetation patterns and imminent desertification in mediterranean arid ecosystems. *Nature*, 449(7159), 213–217.
- Kuehn, C. (2011). A mathematical framework for critical transitions: Bifurcations, fast-slow systems and stochastic dynamics. *Physica D: Nonlinear Phenomena*, 240(12).
- Lamberson, P., & Page, S. E. (2012). Tipping points. *Quarterly Journal of Political Science*, 7(2), 175–208.
- Lenton, T. (2012). Arctic climate tipping points. *AMBIO*, 41(1), 10-22.
- Ludwig, H., Koedam, N., & Dahdouh-Guebas, F. (2009). Global distribution of mangroves: How good or bad its is? *VLIZ Publications*.
- Nagelkerken, I., Blaber, S. J. M., Bouillon, S., Green, P., Haywood, M., Kirton, L. G., ... Somerfield, P. J. (2008). The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquatic Botany*, 89(2), 155-185.
- Naskar, K., & Mandel, R. (1999). *Ecology and biodiversity of indian mangrove vol. i global status vol. ii morpho - anatomy of mangroves*. Delhi: Daya Publishing.
- On s-curves and tipping points. (2007). *Technological Forecasting and Social Change*, 74(6), 715 - 730.
- Papangelou, F. (1974). The conditional intensity of general point processes and an application to line processes. *Zeitschrift für Wahrscheinlichkeitstheorie und Verwandte Gebiete*, 28(3), 207-226. doi: 10.1007/BF00533242
- Pawar, P. R. (2013). Monitoring of impact of anthropogenic inputs on water quality of mangrove ecosystem of Uran, Navi Mumbai, West coast of India. *Marine Pollution Bulletin*, 75(1A), 291 - 300.
- Rietkerk, M., Dekker, S. C., de Ruiter, P. C., & van de Koppel, J. (2004). Self-organized patchiness and catastrophic shifts in ecosystems. *Science*, 305(5692), 1926-1929.
- Ripley, B. D. (1977). Modelling spatial patterns. *Journal of the Royal Statistical Society. Series B (Methodological)*, 172–212.
- Roy, P., Sharma, K., & Jain, A. (1996). Stratification of density in dry deciduous forest using satellite remote sensing digital data- an approach based on spectral indices. *Journal of Biosciences*, 21(5), 723–734.
- Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., ... Sugihara, G. (2009). Early-warning signals for critical transitions. *Nature*, 461(7260), 53–59.
- Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, 413(6856), 591-596.

- Tomlinson, P. B. (1994). *The botany of mangroves*. Cambridge University Press.
- Turner, R. (2009). Point patterns of forest fire locations. *Environmental and Ecological Statistics*, 16(2), 197-223. doi: 10.1007/s10651-007-0085-1
- van Lieshout, M. N. M. (2000). Point processes. In *Markov point processes and their applications* (p. 1-42).
- van Lieshout, M. N. M. (2011). A j function for inhomogeneous point processes. *Statistica Neerlandica*, 65(2), 183–201.
- van Lieshout, M. N. M., & Baddeley, A. J. (1996). A nonparametric measure of spatial interaction in point patterns. *Statistica Neerlandica*, 50(3), 344–361.
- Van Nes, E. H., & Scheffer, M. (2007). Slow recovery from perturbations as a generic indicator of a nearby catastrophic shift. *The American Naturalist*, 169(6), 738–747.
- Vijay, R., Sardar, V., Dhage, S., Kelkar, P., & Gupta, A. (2010). Hydrodynamic assessment of sewage impact on water quality of malad creek, mumbai, india. *Environmental Monitoring and Assessment*, 165(1-4), 559-571. doi: 10.1007/s10661-009-0967-9
- Wassmann, P., & Lenton, T. (2012). Arctic tipping points in an earth system perspective. *AMBIO*, 41(1), 1-9.
- Werners, S. E., Pfenninger, S., van Slobbe, E., Haasnoot, M., Kwakkel, J. H., & Swart, R. J. (2013). Thresholds, tipping and turning points for sustainability under climate change. *Current Opinion in Environmental Sustainability*, 5(3–4), 334 - 340. (Open issue)
- Wiegand, T., & Moloney, K. A. (2013). *Handbook of spatial point-pattern analysis in ecology*. CRC Press.

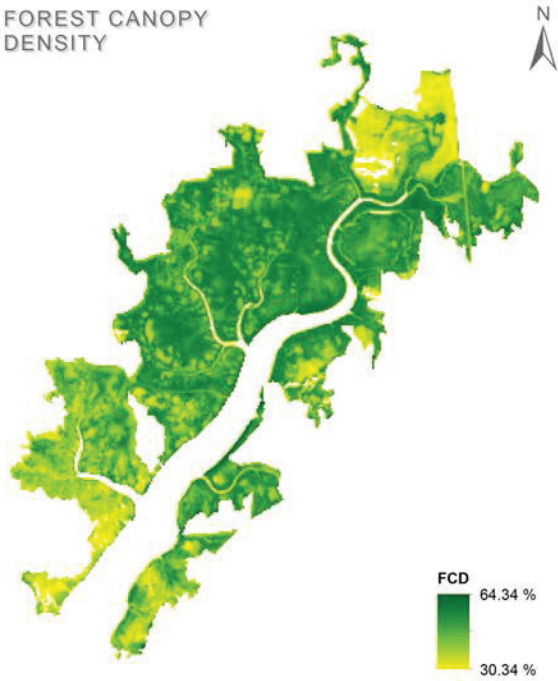


## **Appendix A**

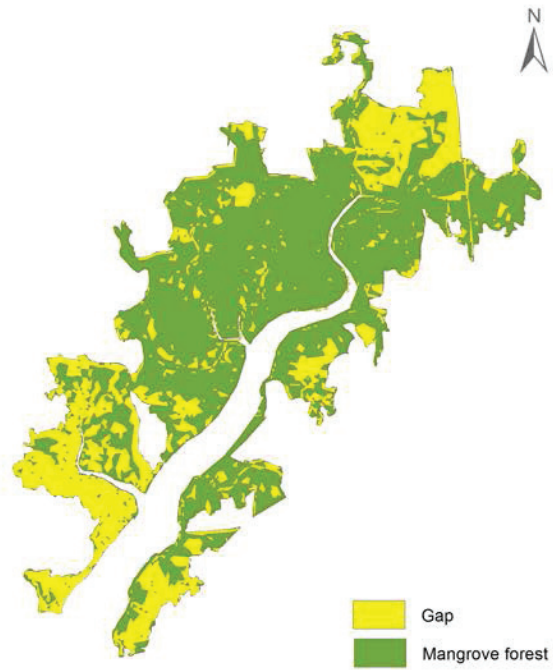
# **Maps of degradation modelling for statistical analysis.**

SITE 1: MANORI GORAI MANGROVE FOREST

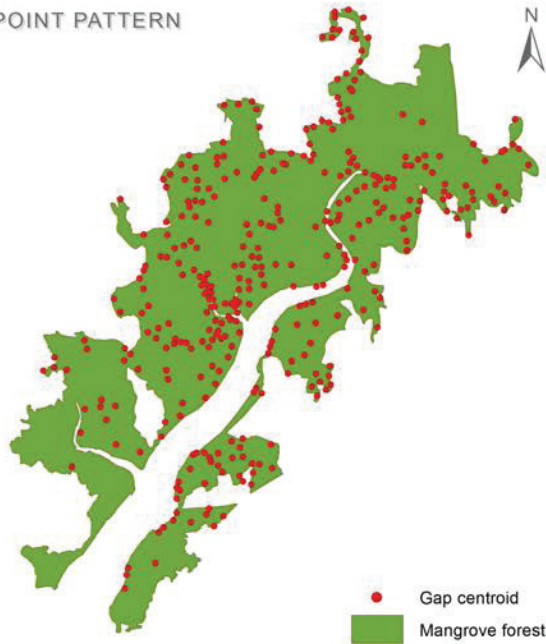
FOREST CANOPY DENSITY



CANOPY GAPS

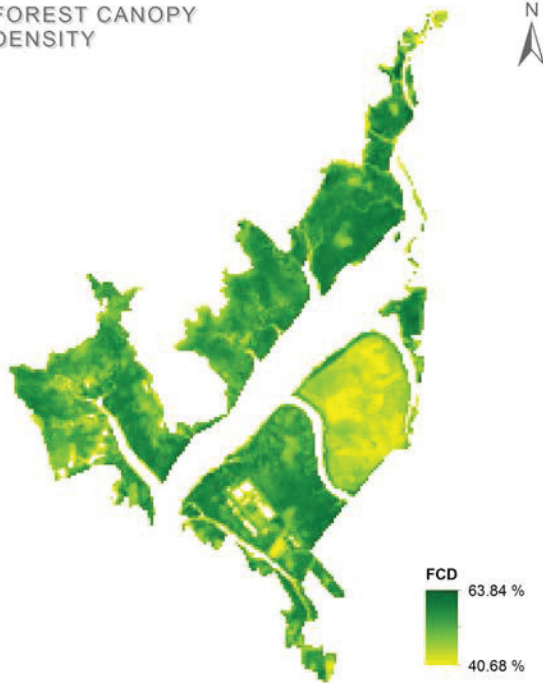


POINT PATTERN

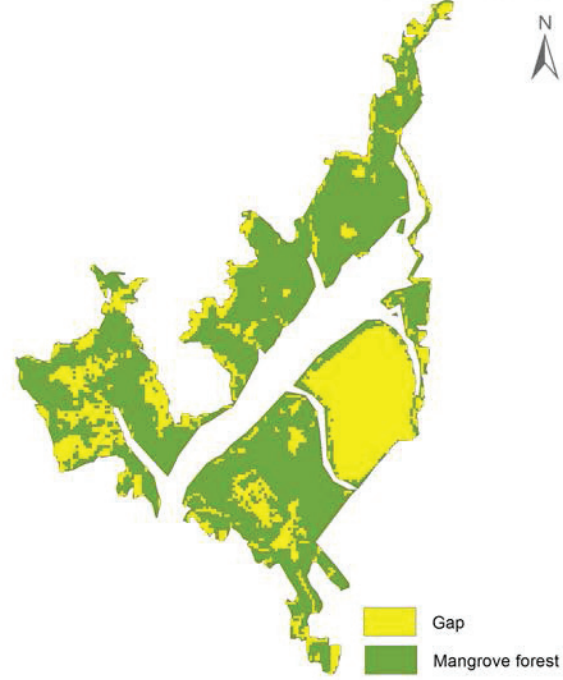


SITE 2: MALAD MANGROVE FOREST

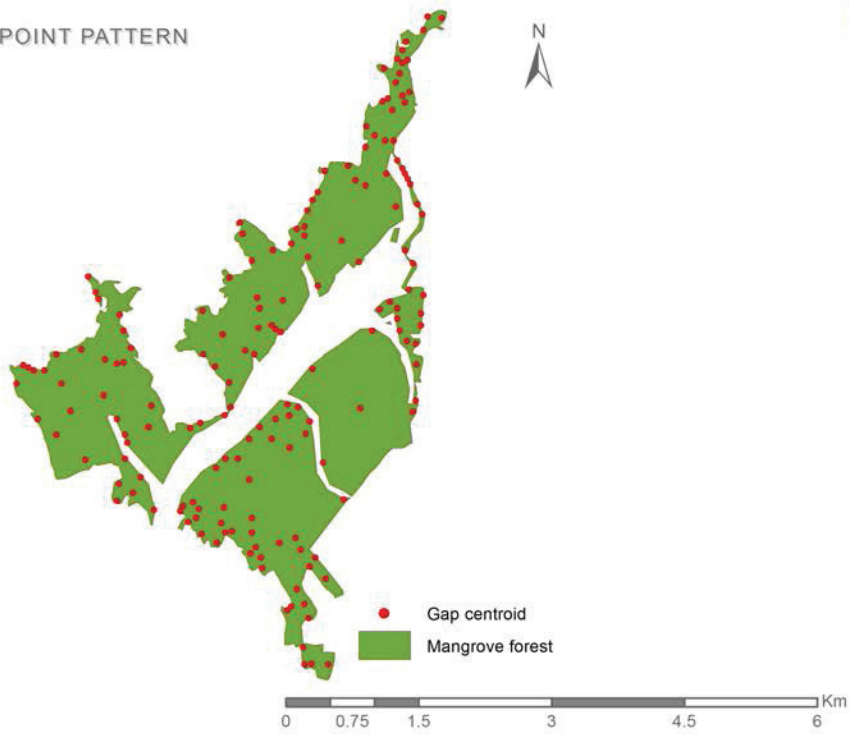
FOREST CANOPY DENSITY



CANOPY GAPS

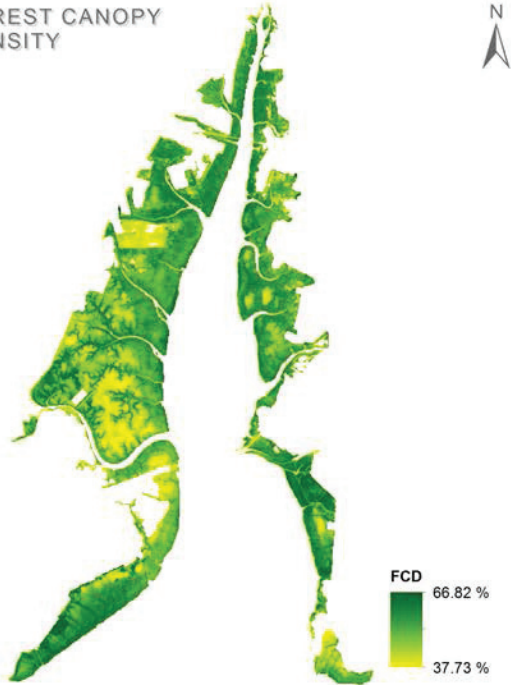


POINT PATTERN



SITE 3: THANE MANGROVE FOREST

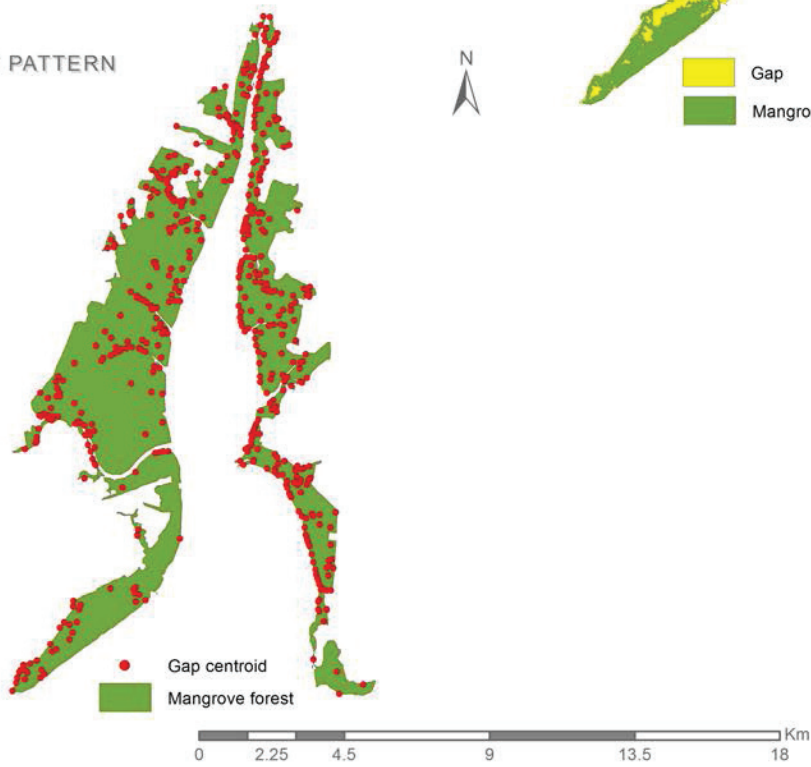
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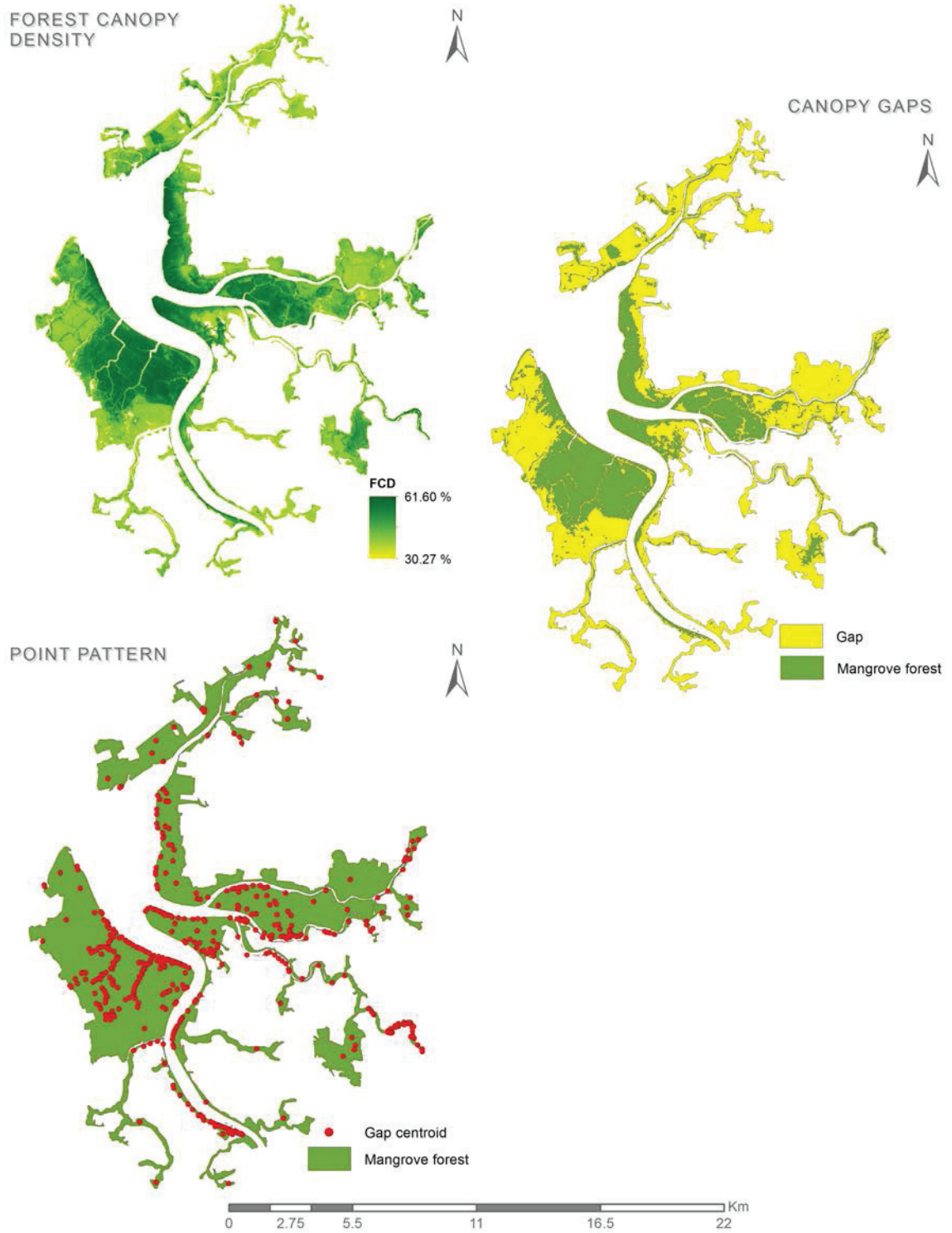
CANOPY GAPS



POINT PATTERN



SITE 4: DHARAMTAR MANGROVE FOREST





## Appendix B

# J-function plot for FCD thresholds

