Exploratory analysis of spatial and temporal movement patterns of black capuchin monkeys in Brazil Atlantic Forest

by

YU LUO

(Under the direction of Lan Mu)

Abstract

Primatologists often meet the challenge of how to interpret the complex high resolution GPS-collected movement points, which include space, time and attribute aspects. Using the tracking data of a group of black capuchins (*Sapajos nigritus*) in Atlantic Forest, we firstly quantified the movement to environment variables and path properties at different temporal scales. Then we developed innovative visualization techniques such as space-time aquarium, attribute clock, and time-time plot to represent spatial, temporal and attribute information of the trajectories within a GIS framework. Comparison of the movement patterns is made between April (fruit-abundant month) and May (fruit-scarce month). Finally, we integrated all the functions into one exploratory data analysis toolbox. The general behavior patterns of the group of monkeys under different environmental scenarios are identified. The results have also shown the effectiveness of the proposed visualization techniques in the exploratory analysis of large movement dataset.

Index words: Exploratory data analysis, space-time trajectories, black capuchin monkey, geographic information system (GIS), behavior patterns

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YU LUO

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by

Yu Luo

Approved:

Major Professors: Lan Mu

Committee: Marguerite Madden
Thomas R. Jordan

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
August 2012

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Yu Luo

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Chapter 1

Introduction

Primates are considered ideal subjects for spatial cognition research because of their high level of physical dexterity and sharp intellect. Diverse research has investigated different aspects of the primates, including their social hierarchy (Sapolsky, 2005), learning ability (Bartus et al., 1979), and memory (Sands & Wright, 1980). Most of these studies are conducted in laboratory environments, and such settings make it very difficult to fully capture the primates' behavior due to spatial constraints. With the recent emergence of location-aware devices and GIS (Geographic Information System) technique, scientists are able to track the real-time movement of the primates over large spatial extents with a higher degree of accuracy. The initial products of GPS-tracking (Global Positioning System) are high resolution points with spatial, temporal and attribute information. This has led to a fundamental question: how can we better interpret the "point clouds" to better understand primates' movement pattern?

1.1 Animal's Trajectory

To better analyze movement points, they are always connected to a trajectory based on time series. Trajectory, according to Andrienko & Andrienko (2005), can be defined as the path made by the moving entity through the space in which it moves. People have always been interested in observing the moving trajectories around us, including the bee's waggle dance (Riley, Greggers, Smith, Reynolds, & Menzel, 2005), ants' routing (Crist & MacMahon, 1991), and birds' migration paths (Tracey, Woods, Roshier, West, & Saunders, 2004). A detailed knowledge of motion patterns can help to better understand animals' behaviors, with implications for the study of spatial cognition. Additionally, the environmental interactions attached to the trajectories are important sources of natural ecosystem dynamics. For example, the spread of avian flu has been proved to be highly correlated with birds' annual migration routes (Peterson, Benz, & Pape, 2007).

Various methods have been developed to observe and record animals' trajectories. Over several decades, due to the technological limitation, tracking has been a tedious and expensive task. One common way of tracking the animal is *mark-recapture* (Turchin, 1998), in which the animals are captured, marked, released and recaptured after a certain time period. This brings high level of uncertainty to the animals' tracking. Therefore, most animal movement studies focus on moving entities that are easy to observe, such as insects (Kareiva & Shigesada, 1983a) and farm livestocks (Graham, 1978). The use of VHF (very high frequency) radio telemetry, to some extent, facilitates the "capture" and "recapture" of animals by collaring them with radio transmitters and by searching their locations with special signal receivers (Mech & Barber, 2002). It is the emergence of GPS technology that revolutionizes the tracking in wildlife biology (Hulbert, 2001). It makes the relatively fine scale real-time tracking of animal movement possible. With the high temporal granularity data, researchers are capable of monitoring both animals' behaviors and their interactions with the surrounding environment(Handcock et al., 2009). For instance, novel TrackTag^{TM} GPS loggers have been used to track the sea bed depth that the sea turtles frequently stay, aiming at better habitat management of the turtles(Schofield et al., 2007) .

While the use of high-resolution trajectories has created new insights into the research of animal behavior and ecosystem dynamics, the measurement and analysis of the complex mobile objects dataset become one challenge. Generally, the multiple points collected by a location-aware device consist of three aspects: the paths indicating motions over space and time, the characteristics of a motion, including speed, direction and length, and the environmental factors associated with the paths such as slope and aspect. Andrienko (2010a) formulates them as $S \times T \rightarrow A$, where S stands for space (geographic coordinates), T stands for time (the data sampled intervals), and A stands for the attributes (both internal and environmental components) attached to the corresponding S and T.

In order to answer the question "how do we analyze the movement data?", the first step is how to better represent space (S), time (T) and attribute (A). Most current GIS programs work well in representing the spatial distribution of the motion points. Since most of them are developed on the basis of cartography's static snapshot view, they often fall short in the representation of dynamic motion data. Three possible solutions to represent dynamic phenomena in the static cartographic world would be interaction, animation and hypermedia (MacEachren & Monmonier, 1992). Animation has been widely used in climatology to display the weather dynamics, such as the tracks of the tropical cyclones (Liu, Wang, Gong, Chen, & Peng, 2006; Patterson & Cox, 2005) and temperature changes (NOAA, 2012). Each map display shows events that take place at specific moments and correspondingly updated as time goes by (Peter, 2004). With hypermedia, the change can also be presented in the snapshot views at different time stamps on one big screen, which enable us to visually identify the differences at time domain (Andrienko, Andrienko, & Gatalsky, 2000).

Other than the techniques mentioned above, Hagerstrand's time geography framework

(Hagerstrand, 1970) is an alternative choice. Its basic idea is to represent the space-time path in a three-dimensional aquarium, where the horizontal axes indicate the geographic space with an independent vertical axis representing the time. The space-time cube has been widely used in space-time movement studies, most of which are about the exploratory analysis of human's daily activity (Kwan, 2002; Vrotsou, Ellegard, & Cooper, 2007). This aspect will be discussed more in Chapter 2.

1.2 Black Capuchin Monkey

"Capuchin monkeys are medium-sized, robusted built monkeys that exhibit moderate sexual dimorphism, and have arms and legs of nearly equal length, large brain-to-body ratios and furry semi-prehensile tails. "(Fragaszy, Visalberghi, & Fedigan, 2004, p. 13). The capuchin monkeys belong to the subfamily Cebinae. Their geographic distributions range from Central America and South America to Northern Argentina. The taxonomic classification of capuchins has long been highly controversial (Amaral, Finotelo, De Oliveira, Pissinatti, Nagamachi, & Pieczarka, 2008). Lynch Alfaro et al. (2012) proposed a classification system to divide capuchins into two genuses, *Cebus* and *Sapajus*, which has been widely adopted.

The group of monkeys studied in this project is *Sapajus nigritus*. As described by Fragaszy et al. (2004, p. 15): "It has a very dark brown or gray, even blackish body with no (or very vague) dorsal stripe. Its limbs are darker than its body and its underside is deep reddish with black overlay. The face is white and contrasts with the rest of the body. The cap is dark and tufts are evident; tufts can be erected or directed sideways or ahead". Figure 1.1 is a photo of *Sapajus nigritus* taken in the study area.

Because of the habitat destruction, hunting and unregulated trade of monkeys, the capuchins population have undergone dramatic decline. Continuous deforestation is the most significant factor causing the vulnerable status of capuchins. Chapman & Peres (2001) has

Figure 1.1: *Sapajus nigritus*. Photo taken by Dr. Andrea Presotto (Reprinted by permission from Dr. Adrea Presotto, copyright 2012)

reported that the forest loss throughout 1980-1995 was around 9.7% in Latin America. In particular, the Atlantic rain forest is now considered to be a significant place for conservation of the black capuchin monkeys. According to an International breeding program, coordinated by an International Recovery and Management Committee established by the Brazilian Government, *Sapajus nigritus* is listed as "vulnerable". Therefore, studying the movement and habitat use of the black capuchin monkeys in this area is essential for their protections.

1.3 Study Area and Data Availability

The data were collected at Carlos Botelho State Park (PECB), which is located in Sao Paulo State, southeastern Brazil (24°00′- 24°15′ S, 47°45′- 24°00′W), within the Atlantic Rain Forest region (Figure 1.2).It is located high up in the Paranapiacaba Mountains, the Guapiara Plateau, in the municipality of Sao Miguel Arcanjo, at an elevation of 720-890 m. The study site is about 380 km^2, connecting three other border parks, forming a continuous protected forest of more than 1200 km^2.

The average annual temperature is around 20°C, ranging from 3°C minimum to 29°C maximum. The climate is relatively mild, with no dry season and a very warm summer (E.N. Domingues & Vellardi, 1987). The landscape composition is rather homogeneous, undisturbed forest dominated by species including families Myrtaceae, Arecaceae, Euphorbiaceae, Leguminosae, Sapotacease, Lauraceae and Rubiaceae (O.C. Negreiros & Netto, 1995). The vegetation at the study site belongs to the domain of 'mares e morros', indicating unpredictable intervals of fructification, occurring for some species every three years or more (AbSaber, 2003). The park is also diverse in terms of fauna. Two other primate species (wooly spider monkeys and howler monkeys) live in the same area.

The population density of capuchins in this park is as low as 2.3 individuals per km^2. The monkey group in this study had 14 individuals, with one dominant male, one adult male, three females, three infants and six juveniles. From the data, the group home range size during 2006, 2007 and 2008 was about 400 ha (Presotto & Izar, 2010).

The environment data includes hydrologic layers, digital elevation data (DEM) at 28×28 m^2 resolution, and remote sensing imaginary from the Landsat 5 Thematic Mapper(TM) at 30×30 m^2 resolution (Figure 1.3).

The black capuchin monkey movement data were collected by Dr. Andrea Presotto in the Sao Paulo Park, covering every month during 2007. Basically, Dr Presotto followed the group of monkeys and recorded the geographic coordinates at the approximate center of the monkey group using GPS every five minutes from around 6:00 am to 6:00 pm on a daily basis. Several years ago, the GPS could easily lose signal in the dense forest areas. Improved GPS technology enables the tracking of the monkey movements in dense forest, with errors of less than ± 10 meters. Such data are ideal for capturing the details of monkey movement. The positions of the monkey group were recorded at five-minute intervals. Sometimes, incomplete data were caused by the monkeys' fast and sudden movement.

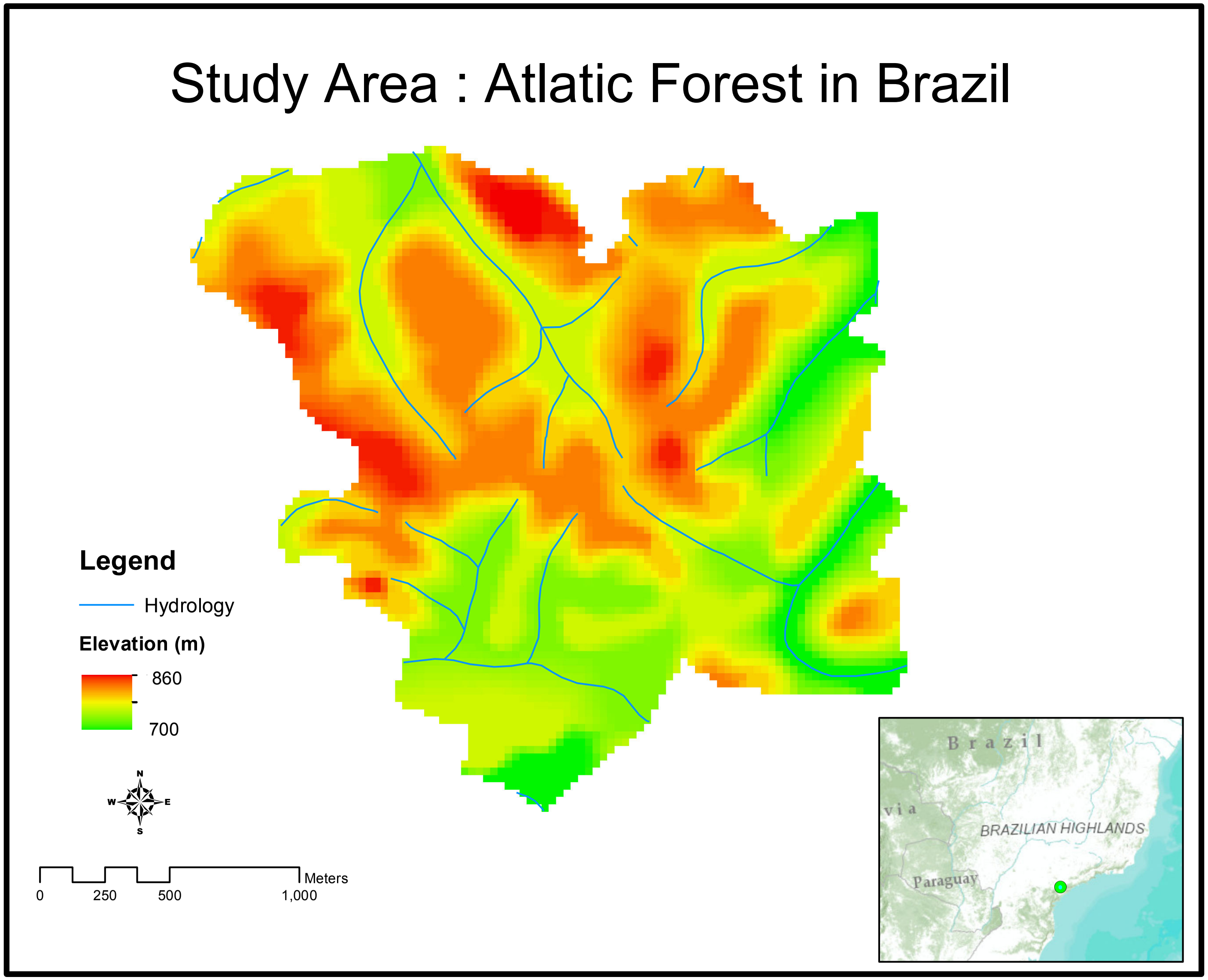


Figure 1.2: The test area at Carlos Botelho State Park with DEM and Hydrologic layers

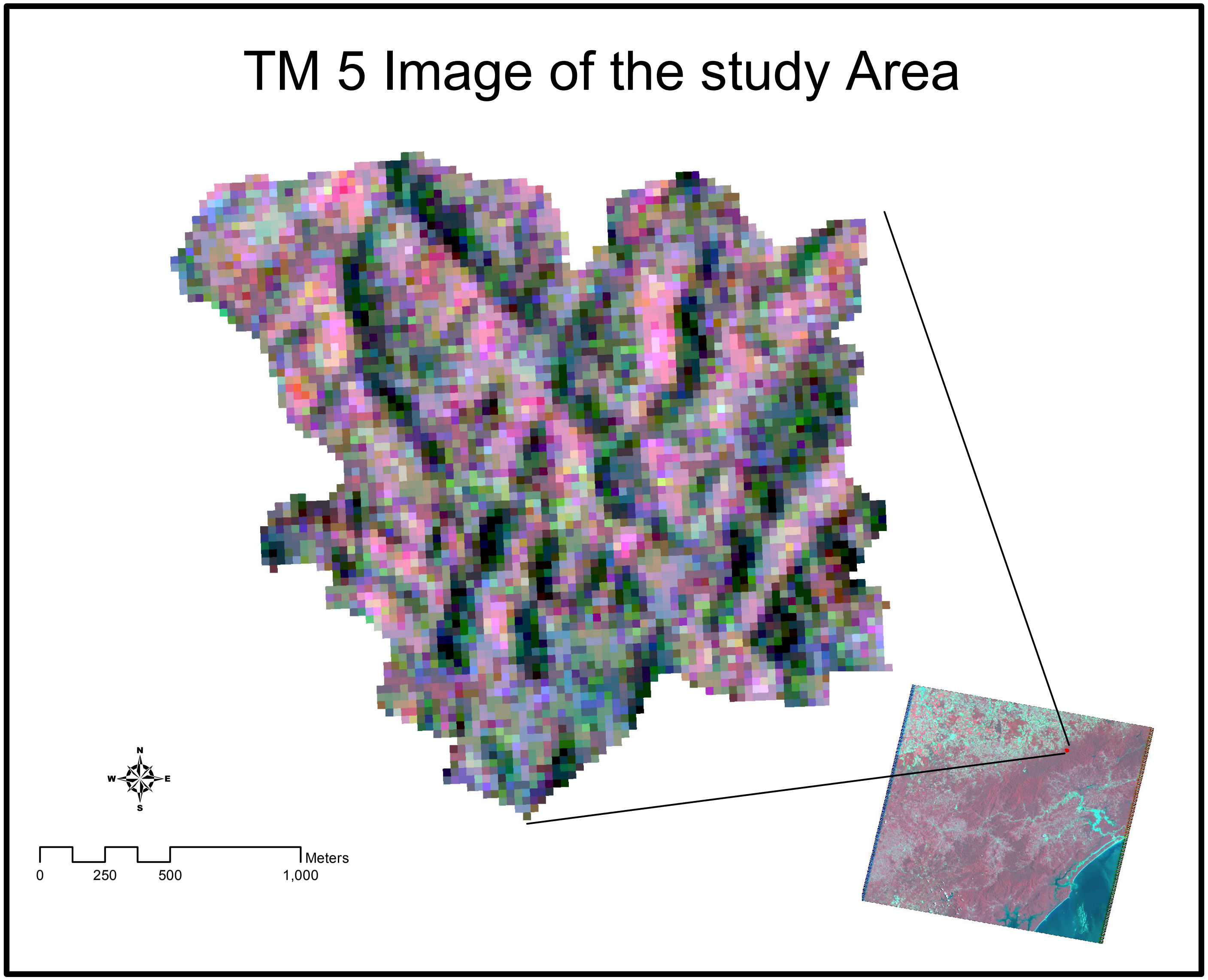


Figure 1.3: Landsat TM5 image of the study area. Pseudo-color combination: band 2: Blue; band 3: Green; band 4: Red

Food is one of the most important driving forces for the animals' movement. The food locations along the paths were also recorded with GPS. According to Presotto (2010), the distance of a monkey's visibility is approximately 80 meters. Therefore, fruit locations within 80 meters were merged together to form food patches. The boundaries of the food patches were recorded. The "food locations" here mainly refer to the fruits the monkeys usually eat. There are fruit-abundant months, such as April when fruits were widely distributed within the study area. In fruit-scarce months, such as May, for example, there was almost no fruit at all and the monkeys had to eat tree leaves. General information with regard to the data used in this study is shown in Figure 1.4.

1.4 Research Objectives

Using high resolution tracking data, this paper focuses on uncovering the space-time pattern behind the moving trajectory over a large spatial extent. The objectives of this paper are:

- To quantify the path with the environmental variables and path properties
- To develop exploratory visualization techniques to help discover the potential spatio-temporal patterns of the movement
- To compare the movement trajectories between April fruit-abundant month (April) and fruit-scarce month (May) to see how the monkeys' behaviors are affected by the environment
- To develop a toolbox to integrate all the functions into an interactive data analysis environment, allowing primatologist to explore the data.

The paper is organized as follows. Chapter 2 reviews the previous work concerning the animal movement and space-time analysis. Chapter 3 describes the unique features of the data and the techniques used to analyze the data. Chapter 4 presents the results of descriptive quantification, exploratory visualization and comparison between April and May.

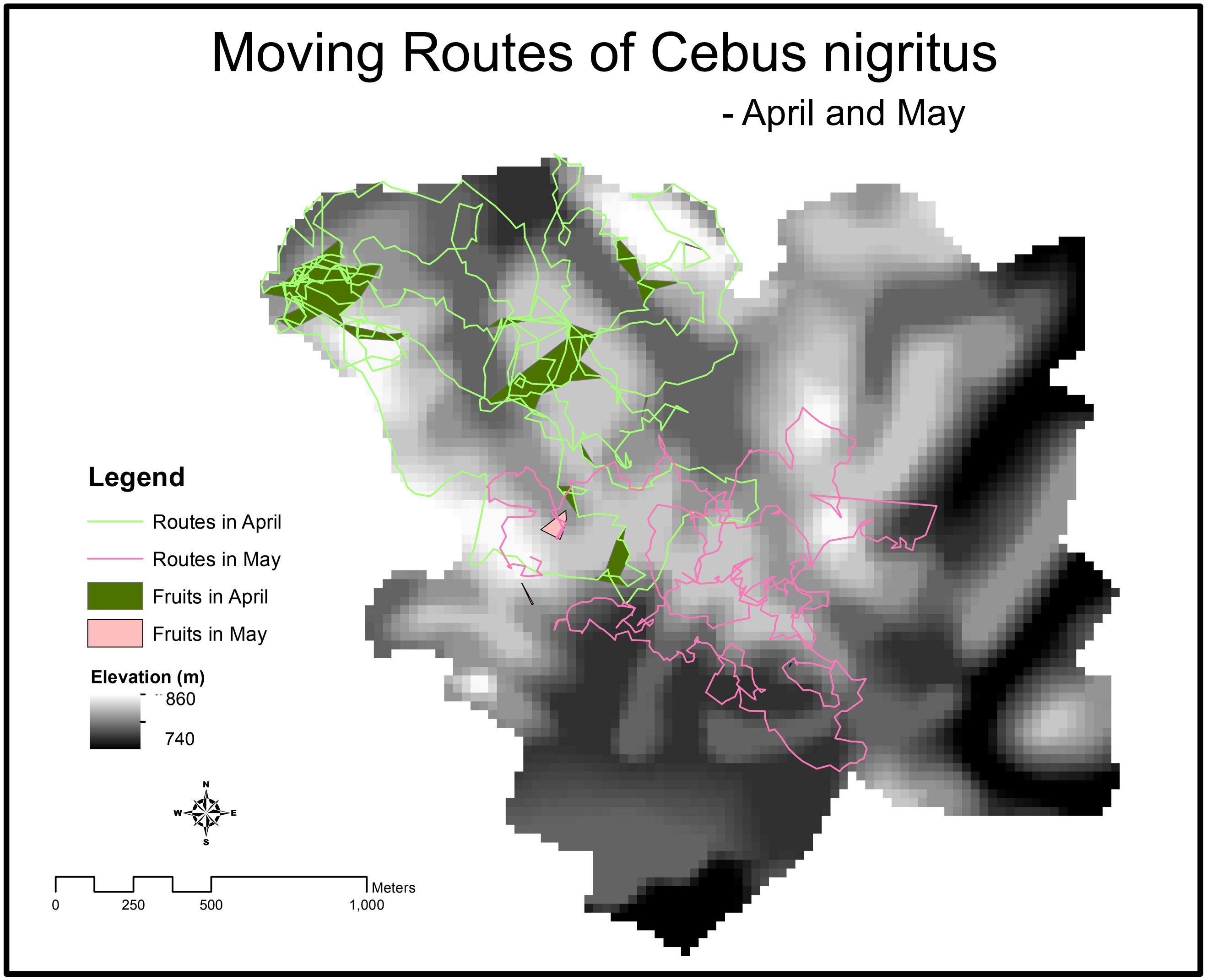


Figure 1.4: Moving routes of *Sapajus nigritus* and food patches in the study area, DEM as the background

Chapter 5 makes a summary of the above work and discuss the potential improvement could be done in the future.

Chapter 2

Literature Review

Studying animal movement plays an important role in diverse subjects, including psychology, ecology and geography. Because of the development of tracking technology, the past decade has witnessed a dramatic increase in the movement research, expanding to all possible species that humans are interested in (Urios et al., 2007; Mellone et al., 2011; Fernandez et al., 2009). Meanwhile, individual-based and spatio-temporal dynamics have been highlighted on the agenda of Geographic Information Science community (McMaster & Usery, 2005). In this project, the animal movement and space-time path analysis are the two most important components; each will be reviewed separately in the following two parts.

2.1 Animal Movement

The spatiotemporal movement of animals is a quite complex research topic which involves multidisciplinary knowledge, including psychology (Gallistel, 1989; Trullier, Wiener, Berthoz, & Meyer, 1997), landscape ecology (Dill, 1987; Nathan, 2008), and geography (Bian, 2000; Goodchild, Yuan, & Cova, 2007). Animal scientists want to settle two main issues: the redistribution of population and the movement of individuals. From the psychology perspective, the animals' cognition and their perception of the surrounding environment determine their motions. From ecologists' view, the movement is primarily driven by various abiotic and biotic factors (Turner & ONeill., 2001), including predators, foods and topographic features. These environmental factors could act as significant constraints, threats or opportunities (Tang & Bennett, 2010) with regard to animal movement. For geographers, the two questions we are mostly concerned are: how do animals use *space* and how do they spend *time*?

2.1.1 The Use of Space

The use of space can also be defined as the ranging patterns. An animal usually has an area that it lives and travels in its everyday activities of food gathering, mating and caring for young. Burt (1943) defined this area as the home range. A knowledge of the home range is a pre-requisite both to the effective management of the animals' resources and the establishment of conservation strategies (O'Brien, 1984).

After identifying the animals' home range, it is also necessary to know their space use patterns within that area, which is often measured by utilization distribution (Jennrich & Turner, 1969). According to Van Winkle's (1975) definition , Utilization distribution is a probability density that represents an animal's relative frequency of occurrence in a 2D (x, y) plane, which is usually constructed with a kernel method. Utilization distribution is a global and static descriptor, which treats the home range as two dimensional. Research has been done to take the third dimension and time into the measurement of utilitarian distribution. Keating & Cherry (2009) described a product kernel model estimation method to handle circularly distributed temporal covariates. Benhamou & Riotte-Lambert (2012) proposed a more dynamics approach to concentrate more on the residence time and visiting frequency, which are referred to as intensity Distribution(ID) and recursion distribution(RD).

When it comes to the movement of monkeys, Terborgh (1983) proposed four possible scenarios that a group of monkeys can explore its home range: 1) if a species' primary food on insects, which are evenly distributed, it is expected to cover the home range homogeneously; 2) at the other extreme, if a species' food sources are highly patchy, such as the fruiting trees, its movement is largely affected by the fruit ripening; 3) a species which needs to defend its resources would spend more time patrolling the boundaries of the home range; 4) if there are some essential but limited resources, movement is more likely concentrated on the core area. In the real world, the animals' use of space is certainly much more complicated and possibly a combination of these models.

2.1.2 The Use of Time

The use of time can be defined as the activity patterns, or temporal behavior patterns. An animal's temporal behavior is significantly associated with metabolism and energetic constraints, which are always in dynamic states due to the temporal variations of ambient environment (Halle, 2000; Zhou, Wei, Huang, Li, Ren, & Luo, 2007). Studying the activity patterns of an animal helps to better understand its physical properties and psychological state (Lewis & Rachlow, 2011). Additionally, by comparing the activity patterns of the same animal under different environmental conditions, such as food distribution(Stevenson, 2001) and weather (Johnson, Edwards, & Ford, 2011) , we can explore the ecological influences on the animal's behavior (Struhsaker & Leland, 1979).

One important measurement of the activity patterns is time budget, which is a list of the percentage of time that an animal spends on different activities. Generally, approximately 95% of an animal's activity in one day can be divided into four categories: feeding, moving, social interaction, and resting (Hill, 1999). The percentages of different activities have been used in various animals' research (Huang, Wei, Li, Li, & Sun, 2003; Goodman, 2007; Tang, Zhou, Huang, Meng, & Huang, 2011). Many potential environmental factors have been proposed to explain the variations of time budgets, including temperature (Hogan et al., 2011), humidity (Vieira, Baumgarten, Paise, & Becker, 2010) and food availability (Caselli &

Setz, 2011; Rothenwohrer, Becker, & Tschapka, 2011). Other factors, such as age (Stevenson, 2006), sex (Weiss, Corona, & Schultz, 2012), and social dominance (Hemingway, 1999), have also been proved to be highly correlated to the variations in activity patterns.

Researchers in various fields have demonstrated the monkeys' ability to adjust the time budgets in response to environmental changes, such as seasonal variations of food availability and solar insolation (Chaves et al., 2011; Thoren et al., 2011). Schoener (1971) concluded three possible adjustments in time budgets during food scarcity: 1) increase the time for subsistence, 2) increase feeding time, 3) reduce the time allocated to high energy-consuming behaviors.

Both the ranging patterns and activity patterns are related in multiple ways with the animals' physical characteristics, social behavior and external environment factors. Therefore, it is necessary to take both space and time into consideration in the analysis of animals' movement.

2.2 Space-Time Path Analysis

According to Peuquet (1994), the spatio-temporal data include three major components: space, time and objects. Each component has its own properties and is highly interrelated with each other. A similar statement related to the movement is that "a trajectory of a single entity is a configuration of locations (possibly, in combination with the secondary characteristics of movement)" (Andrienko, Andrienko, Pelekis, & Spaccapietra, 2008, p. 4). Recent major shift in geographic science from place-based perspective (Katerina, 2007; Klepeis et al., 2001) to individuals is highlighted by the emergence of location aware devices. This emphasizes that Geographic Information Science is not only about locations, but more importantly, about mobility.

While traditional GIS works well in static and place-based analysis, they often fail to put individuals' behavior and their interaction with the environment in a space-time context (Chen et al., 2011). To fully understand an animal's movement pattern, both space and time components are equally important in the movement analysis.

2.2.1 Visualizing the Movement

The space component of the path can be easily represented with static maps (Kraak & MacEachren, 1994) by projecting the complete trajectory on a conventional planar map (Frihida et al., 2004; McGrady et al., 2003). The time component can be visualized using variations in symbology for different time stamps. The most famous example is the Napoleon's March on Moscow of 1812 - 1813 (Tufte, 1983). Six separate variables were shown in the map. For example, the size of the army is marked with the band width and the time labels were also drawn in the corresponding locations. The color variations, sometimes, can also be used to represent the "ages" of events when the number of time stamps is relatively small (Peter, 2004).

Not until the concept of "time geography" (Hagerstrand, 1970) was used in urban geography research that the movement, inherently temporal, was systematically included in "Geography". Two basic concepts in the time geography framework are "space-time path" and "space-time prism". Hagerstrand argued that time should not be treated as an external factor. Hence he adopted a three dimension coordinate system which use the x and y plane for spatial representation and the vertical z axis for the time. The individual trajectories become sinuous 3D lines which go up as time goes by, forming the space-time paths. The space-time prism refers to the spatial and temporal extent that can be achieved by individuals under specific constraints (Lenntorp, 1976). The time geography framework has been widely applied in human behavior analysis. Kwan used 3D GIS data models for multi-story structures, such as women's studies (Kwan, 2002) and evacuation research (Kwan & Lee, 2005). Tian, Ma, Wang, Song, & Xie (2010) analyzed the spatio-temporal behavior of people based on mobile phone call records.

Some novel techniques are also developed to visualize the movement. One example is the TT plot (Time-time plot), which transforms spatio-temporal data to a 2D plane with two time axes, the spatial components, such as speed, travel distance and directions, are represented with coloring or shading cells (Imfeld, 2000). Andrienko et al. (2010b) applied SOM (Self-Organizing Map), which is a combination of clustering and dimensionality reduction, to link the space and time component and create an integrated visual analytic environment.

2.2.2 Quantifying the Movement

To get in-depth understanding of the movement pattern, the trajectory is better to be represented with numbers. From mathematical perspective, one trajectory can be defined as the curve depicting one animal's relocations (Calenge, Dray, & Royer-Carenzi, 2009). Whereas the movement is continuous, the GPS sampling can only record the location at certain intervals. In this case, the trajectory curve is discretized to a number of steps connecting successive displacements of the animal (Turchin, 1998).

A lot of efforts have been devoted to quantifying such trajectories. The most fundamental level is using a set of descriptive parameters. Calenge et al. (2009) categorized the descriptive parameters into three scale levels: 1) step between two relocations: step length, speed or azimuth (Johnson et al., 2001; Marsh & Jones, 1988a); 2) relationship between two steps: mean squared distance or relative angle (Kareiva & Shigesada, 1983b; Zollner & Lima, 1983); 3) trajectory: path length or sinuosity (Simon, 2004; Webb et al., 2009). The first two categories are both in-path variables depicting the dynamics of attributes along the path, while the third one more often considers the trajectory as a whole, or stationary. To narrow the gaps between descriptors of different scale levels, Simon (2004) used sliding windows and divided the trajectory to subparts. The descriptive parameters are calculated within the sliding window. Similarly, Andrienko, Andrienko, & Gatalsky (2000) developed *dynamics interval view* method and apply it in a study of storks migration. Laube, Dennis, Forer, & Walker (2007) proposed a framework to dynamically explore the geospatial lifeline, and identified four lifeline context operators.

Because the turning angles and the sinuosity of the trajectory are important indicators of one animal's space use patterns whether oriented movement (Schooley & Wiens, 2003) or general dispersal wandering (Doerr & Doerr, 2005) within the home range. More linear movement trajectory implies the animal is more in exploratory mode (Fryxell et al., 2008) or searching for dispersal food sources (Webb et al., 2009), whereas more tortuous path indicates the animal is in encamped mode (Fryxell et al., 2008) or habitat assessment (Bartumeus et al., 2005). One simple way to describe the sinuosity is the straightness index ranging from 0 and 1, which is computed as the ratio between the beeline distance and the path length (Batschelet, 2001). Dicke & Burrough (1988) introduced the fractal analysis to measure the sinuosity of random search path as a fractal dimension. The fractal dimension of a path can be estimated as:

$$D = \frac{\log(n)}{\log(n) + \log(d/L)}$$

where n is the number of steps, L is the total path length and d is the planar diameter, defined as the longest distance between two points in the curve. For a random search path, the fractal dimension usually ranges between 1 (curvilinear path) and 2 (fully jagged and wiggly path) (Simon, 2004). The sinuosity of a path can also be estimated based on the distribution of turning angles. As any step of the curvilinear can be considered as a vector, the circular statistics (Fisher, 1993) provides several descriptors to depict the sinuosity, such as mean vector length and mean turning angles (Simon, 2004).

2.2.3 Modeling the Movement

Other than descriptive parameters, various models have also been used to represent the trajectory with mathematic rules and a set of parameters. Models developed in physics, which generate theoretical trajectories by using the last step of one trajectory to build an additional step (Calenge et al., 2009), are commonly used in ecology research, such as correlated random walk (Byers, 2001), biased random walk (Marsh & Jones, 1988b), and Brownian bridges (Horne, Garton, Krone, & Lewis, 2007). Some other models developed in probability have also been widely implemented, such as state-space models (Jonsen, Myers, & Flemming, 2003) and stochastic differential equations (Preisler, Ager, Johnson, & Kie, 2004)

In geographic research, the most commonly used models include system model, cellular model (Nishinari, Kirchner, Namazi, & Schadschneider, 2004), and agent-based model (Boyer & Walsh, 2010). Among them, the agent-based model is the most widely used for animal movement research. Generally it simulates the behavior of individuals, interactions among individuals, and interactions between individuals and their environments within geographic frameworks. There are four key components in animal movement: internal states, external factors, motion capacities and navigation capacities are always identified as the factors that affect the agents' movement (Tang & Bennett, 2010). Although agent-based modeling is considered to be an ideal solution for the animal movement study, it is far away from an exact simulation of the animals' actual motion. Actually none of the models mentioned above are capable of capturing the complexity of the animals' behavior (Calenge et al., 2009). Most of the case, they are used as the reference to the observed trajectories.

2.3 Motivation and Need of Research

The movement of animals, especially primates, has been widely studied by psychologists and ecologists. The general research topics include the animals' food searching strategy (exploratory or encamped), internal navigation system (allocentric or egocentric), and the environmental driving factors. On the other side, the space-time aquarium is commonly used in depicting the individual trajectory in human geography. However, there is much less research that analyzes the animal's movement within both spatial and temporal constraints. Motivated by this, we plan to study the black capuchin monkeys' movement from space and time perspectives: how they use space and how they spend time. The design of the whole research framework is space-time oriented.

This project firstly represents the movement trajectories of a group of black capuchins within a GIS framework. The movement points are connected to form the polylines, which would then be projected to space-time aquarium to integrate both space and time components in one representation. The study also quantifies the paths at different scale levels. Both summary descriptive statistics variables and in-path dynamic variations are calculated. The distribution of turning angles and sinuosity of the path are two important indicators that are particularly studied. To better understand how the environmental factors would influence the black capuchin monkeys' behavior patterns, the above quantified parameters of fruit-abundant month (April) and fruit-scarce month (May) were compared using two-sample statistical t-test. New visualization techniques (attribute clock and time-time plot, are developed to facilitate the exploratory data analysis of the attributes dynamics) along the paths. Finally, all these functions are integrated into an exploratory analysis environment with regard to the movement data.

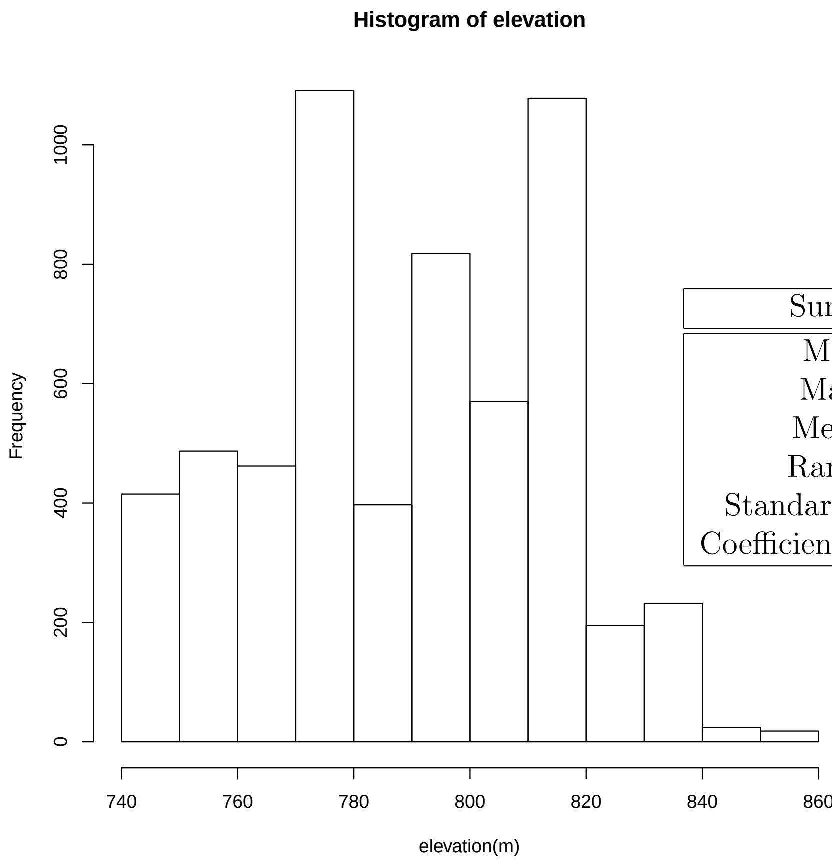
Chapter 3

Methodology

This project analyzes both the space and time perspectives of the black capuchin monkeys' movement, which correspond to their ranging and activity patterns. The geographic visualization techniques, including both maps and charts, are primarily used to examine the potential patterns behind the trajectories.

3.1 Unique Features of the Data

There are several unique features about the study area and the black capuchin monkeys. Firstly, monkeys are highly intelligent animals. We are not completely clear about how efficient they are in route navigation (Presotto & Izar, 2010) and food locations memorization (Basile, Hampton, Suomi, & Murray, 2009), however, they will definitely not follow a simple pattern as the "Game of Life" (Gardner, 1970) does. Secondly, the moving range of the monkeys during the data collection period is relatively small. The spatial extent of their activity during the entire year of 2007 is about 4.6 km^2. The terrain within the home range is relatively undulating, but not too steep (Figure 1.4 and 3.1). Figure 3.2 is the normalized difference vegetation index (NDVI) calculated from Landsat TM5 image. The histogram and summary statistics of the NDVI (Figure 3.3) shows that there is no obvious landscape heterogeneity across the study area. Hence the movement can be categorized as small scale movement (Webb et al., 2009), which is largely driven by physical habitat features and resource availability (Crist et al., 1992; McIntyre & Wiens, 1999). Thirdly, in the dense forest, the monkeys have low visibility. This low visibility would inevitably increase the uncertainty of the monkeys' movement. As shown on the routes map (Figure 1.4), the trajectories are quite randomly distributed over the whole study area, unlike the movement patterns in northern Brazil (Hinely, 2006), which is savannah region with high visibility.



Summary	Value
Min(m)	740
Max(m)	860
Mean(m)	790.409
Range(m)	80
Standard deviation	25.79498
Coefficient of variation	0.03263498

Figure 3.1: Histogram and descriptive statistics of the elevation in the study area

In view of the unique features mentioned above, also considering that the data set is quite large and the typical structure is unclear, this study focuses on the exploratory analysis,

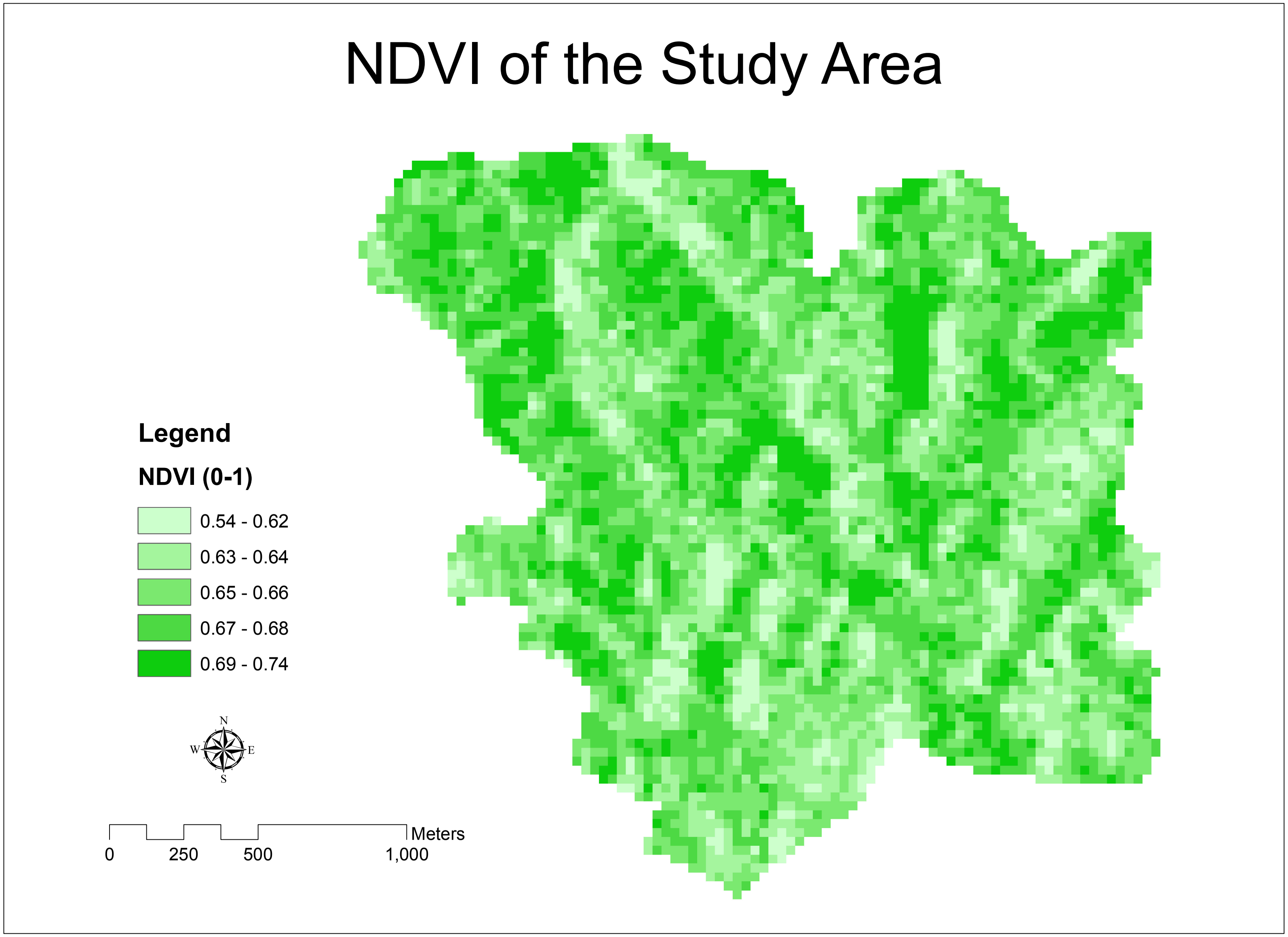
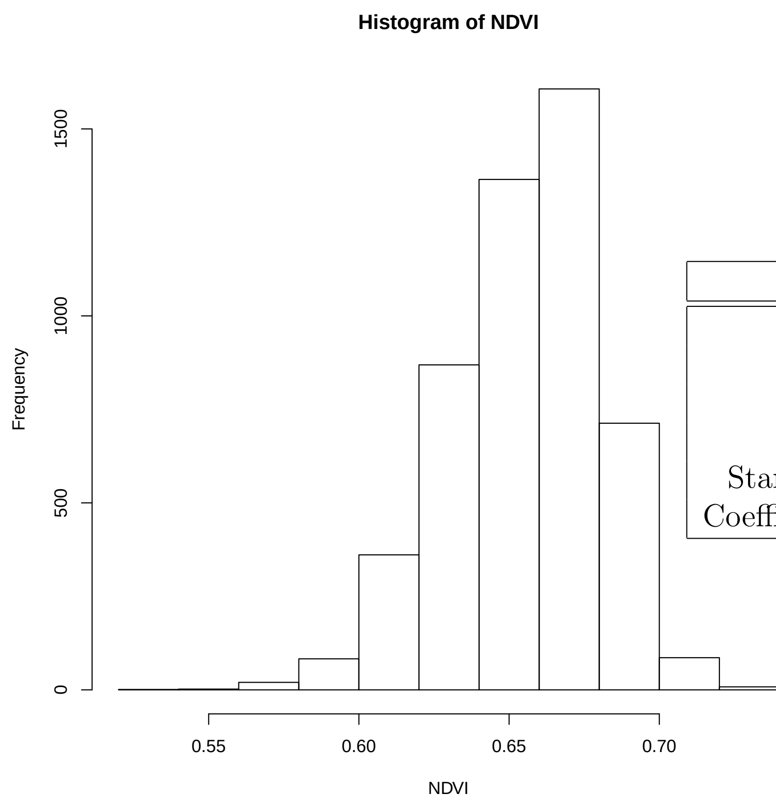


Figure 3.2: Normalized Difference Vegetation Index of the Study Area. Calculated from Landsat TM5 (Band4 - Band 3)/(Band4 + Band3)

including data quantification, query and visualization.

The movement data in this project are collected using a constant time lag (5 minutes), which is often defined as “regular trajectories”. In other words, at every five minutes interval, no matter whether the monkeys relocate or not, there is a record at that point. According to Dr. Presotto, there could be some missing records, either due to the monkeys’ unremitting activeness or simply because the followers need to stop for food. For those time stamps, the locations of the monkeys are estimated as the previous time stamps location in the data preprocessing. Then descriptive variables are calculated at different scales to represent the trajectories with numbers. Exploratory visualization techniques are applied to examine the attribute dynamics both spatially and temporally. Finally, all the functions will be integrated in an interactive data exploration environment to facilitate the future data analysis.



Summary	Value
Min	0.5384616
Max	0.7377049
Mean	0.6552062
Range	0.1992433
Standard deviation	0.0252134
Coefficient of variation	0.03848163

Figure 3.3: Histogram and descriptive statistics of the NDVI in the study area

3.2 Movement Path Quantification

According to Andrienko et al. (2010a), the movement data can be formulated as $S \times T \to A$. In other words, the collected GPS points consist of space, time and attribute information. The S (space) is recorded with series of point coordinates (x, y, z) and the T (time) is the time stamp while recording the corresponding location. The A (attribute) includes both the internal properties of the path and the external environment factors along the path. The quantification of the trajectories will be conducted from these two perspectives.

3.2.1 Environment factors

The movements of black capuchin monkeys are highly likely to be influenced by the topography environment, solar azimuth, food distribution or water sources. Therefore, we used the elevation (DEM), hydrology, food patches and Landsat TM5 images of the study area. In order to study movement, these environmental factors need to be quantified and assign to the routes. For the topography, the elevation and the slope could important indicators of the energy consumption. The DEM can also derive the hill aspect layer, which would tell us the solar azimuth at each point. With proximity analysis in GIS, we will also keep tracking the monkeys' distance to the nearest food patches and the water sources. The NDVI values are derived from the Landsat TM5 image, and then assign to each recording point to see if there could be any potential patterns.

Other than above data, we also got some background information, such as the temperature and precipitation data. While most of them are monthly average values and might not be that accurate, still, they could be used as a reference for the general background environment conditions.

3.2.2 Path Properties

The trajectory can be considered as a polyline curve, hence can be depicted with various geometrical variables. Because the data in this project are regular trajectories, the descriptive parameters can be calculated at different scale levels.

At the step level, each step has the properties of the relocated distance, speed (the step length divided by the time lag) and step orientation (the absolute angles between the step and the referenced direction). At the inter-step level, we can quantify the paths with the turning angles (the angles between the new step direction θ_{i+1} and previous step direction θ_i, $\alpha_i = \theta_{i+1} - \theta_i$). As a trajectory is constructed from each single step, the descriptive parameters at step level and inter-step level can also be computed at trajectory levels, such as the length of the trajectory, the average speed and the overall heading direction. The three scale levels are never independent. One trajectory can be the path of a whole day, or just one step or the combination of several steps. Similarly, the inter-step can be the relationship between steps, or between subparts of the trajectory. Therefore, in order to narrow the gap between these three levels, the sliding window method is implemented. The temporal granularity of the descriptive can be flexibly controlled by the size of sliding window (Figure 3.4).

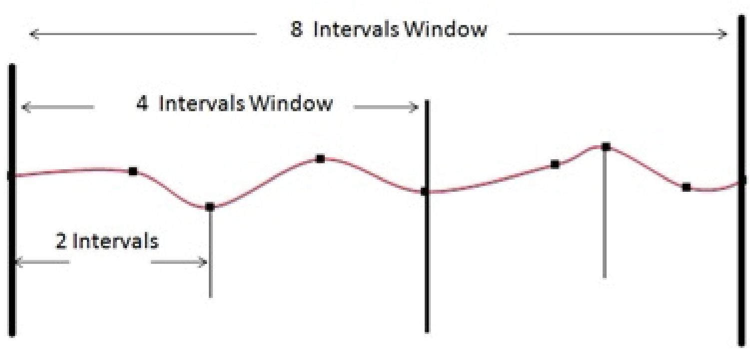


Figure 3.4: Moving Window

Because the turning angles are important indicators of the efficiency of the monkeys' moving strategy, the angular quantification of the paths is a main focus of this study. The simple straightness index is firstly calculated as D/L, where D is beeline distance between first point and the last point, and L is the length of the trajectory. As the fractal analysis is often considered to be an alternative and promising technique to measure the sinuosity of the path (Simon, 2004), the fractal dimensions of the trajectories are also calculated. The circular statistics is also used to depict the distribution of turning angles. Each discrete step can be characterized as a vector in Cartesian coordinate system. The mean vector is a summary descriptive variable of n step vectors. Its angular values ξ can be characterized as the mean cosine and mean sine:

$$c(\xi) = \sum_{i=1}^{n} \cos(\xi_i)/n = r(\xi)\cos[\phi(\xi)]$$

$$s(\xi) = \sum_{i=1}^{n} \sin(\xi_i)/n = r(\xi)\sin[\phi(\xi)]$$

The mean vector orientation $\phi(\xi) = \arctan_3[s(\xi), c(\xi)]$ [1] measures the angular mean, and the mean vector length $r(\xi) = [c(\xi)^2 + s(\xi)^2]^{0.5}$ measures the concentration of the distribution around the mean, ranging from 0 (dispersed distribution, random walk) to 1 (punctual distribution, straight line movement).

Besides all the geometric variables, the internal attribute of the movement also includes the activity of the monkeys, represented as nominal values. The activity patterns are generally divided into two categories: Eating and Non-Eating, which are correspondingly assigned the value 1 and 0.

After quantification, it is necessary to put the numbers into one context that actually makes the numbers meaningful. To do that, we compared the descriptive parameters under two

[1] $\arctan_3(s, c)$ is defined as $\arctan(s/c)$ for $s > 0, c > 0$; $\arctan(s/c) + 180°$ for $c < 0$; $\arctan(s/c) + 360°$ for $s < 0, c > 0$

scenarios: April (fruit-abundant, high temperature) and May (fruit-scarce, low temperature) to see if the environment factors would influence the black capuchin monkeys' ranging strategies and activity patterns.

3.3 Exploratory Data Visualization

The movement data are usually quite complex, since they include the spatial, temporal and both internal and external attribute information. As the data volume is large and the typical patterns remain unclear, this project focuses on the exploratory data analysis (EDA) at this stage. Tukey (1997) defined EDA as using a set of descriptive and graphical tools to discover patterns of the data and suggest hypotheses. Users can view different perspectives of data by interactively adjusting the parameters and representation techniques. In GIS study, due to the nature of geographic data (Dykes & Mountain, 2003), visualization is a particularly significant technique to promote human's analytical capability and facilitate the interactive data analysis. We applied three graphical techniques (space-time aquarium, attribute clock and time-time plot) to improve our understanding of the spatio-temporal movement patterns of black capuchin monkeys.

3.3.1 Space-Time Aquarium

The 3D space-time aquarium is developed based on the 2D static map. To integrate the time component to the representation, an additional vertical axis is imposed to 2D maps. The geographical locations (x,y) are represented with two horizontal axes, the third dimension value z will go up as the time stamps increase. Details about space-time have been discussed in the Chapter 1 Introduction and Chapter 2 Literature Review.

Considering the data will be analyzed within a GIS framework, the ArcGIS 10 (ESRI) is used as a platform to integrate all the functionalities. The space-time aquarium is a

3D representation of data, so the paths will be drawn in ArcScene environment. The time stamps are firstly converted to numeric values proportionally based on the temporal range and granularity. For example, the approximate wake-up time of the monkeys 6:00 am can be set to the origin 0 along time axis, and five minute sample interval can be 1 unit increment in z value. The Python script is written to connect the points to 3D lines based on the numeric time sequence. In addition to simple visualization of the 3D trajectories, this study went a step further to add interactive query function, so that the users can select the time range they are interested in and display the relevant attributes dynamics during that period.

3.3.2 Attribute Clock

Batty (2006) proposed a way to visualize the ranking changes along the time line by projecting the "ranking trajectory" to a clock. The radius represents the values and the angle is the time stamps. Figure 3.5 are pictures from Batty (2006). With the rank clock, we can get an immediate view of the city rank orders changes, especially from the sample city trajectories (Figure 3.5, right)

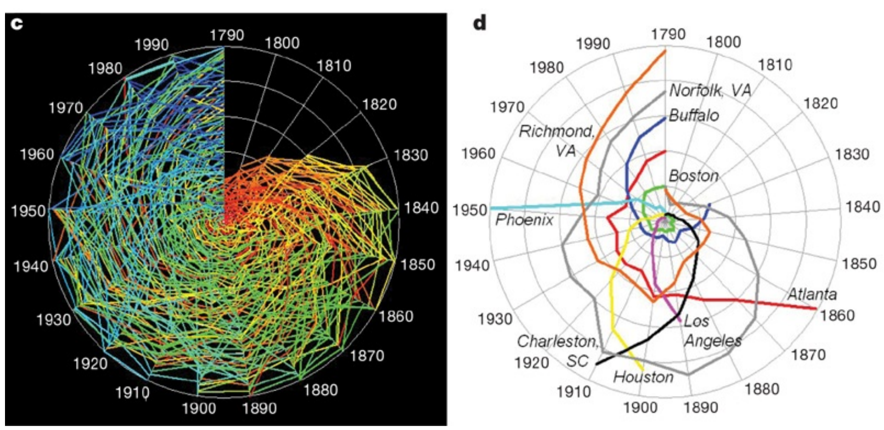


Figure 3.5: Rank clock examples from Batty (2006). Left: rank orders changes of the top 100 cities in US over the past 300 years, the rank order go from 1 (the center) to 100 (circumference); Right: sample city trajectories. (Reprinted by permission from Macmillan Publishers Ltd: Nature, copyright 2006)

Inspired by the rank clock idea, we develop a similar term "attribute clock" to represent the temporal changes of the attributes on a daily basis. The data are collected from around 6:00 am to 6:00 pm, which is exactly 12 hours. This makes it appropriate to plot the data to an actual "clock".

The black capuchin monkeys' frequently stop for food or resting. Therefore, the movement paths are not "continuous" along the time line. Some attributes, such as the speed and step length, dramatically vary from zero to certain values. If we connect the points to form a line, it would result in a really poor visualization. Therefore, we develop the "transparent pie" method to solve this problem. If the monkeys stop during certain period of time, in the attribute clock, the corresponding angle range will be filled with transparent pie, instead of line connection. By overlaying different days' movement data and controlling the transparency of the "pie", we can even get an idea of how frequent the monkeys' stop during specific period of time. More details about "attribute clock" will be discussed in the next Chapter.

3.3.3 Time-Time Plot

The TT-plot is a visualization technique that transforms the 3D motion data to 2D representation by converting the spatial component to an inter-event distance matrix and adding a second time axis (Imfeld, 2000). The inter-event distance can be actual spatial distance or angle difference. The product of the previous one is TT-δ plot, which is mostly used TT plot. The x and y axis are both time, the value at the point t_1, t_2 is the distance δ between two locations P_{t_1} and P_{t_2}. It can be formulated as

$$Z_{TT-\delta} = \sqrt{(x_{P_{t_1}} - x_{P_{t_2}})^2 + (y_{P_{t_1}} - y_{P_{t_2}})^2}$$

Different movement paths will generate different patterns in TT-δ plots. For example, a zero-value point ($t_1 \neq t_2$) indicates that the monkey visit the same place at t_1 and t_2.

Imfeld (2000) used the artificial data to general four movement patterns (Figure 3.6). The TT-δ plots are symmetrical along the diagonal line, where the values are zero (distance between horizontal t_x and vertical t_x). The TT-δ plot require certain degree of interpretation. Take the Figure 3.6b as an example, the blue line parallel to diagonal line implies that the monkeys walked the same path in the same direction as it did some time ago.

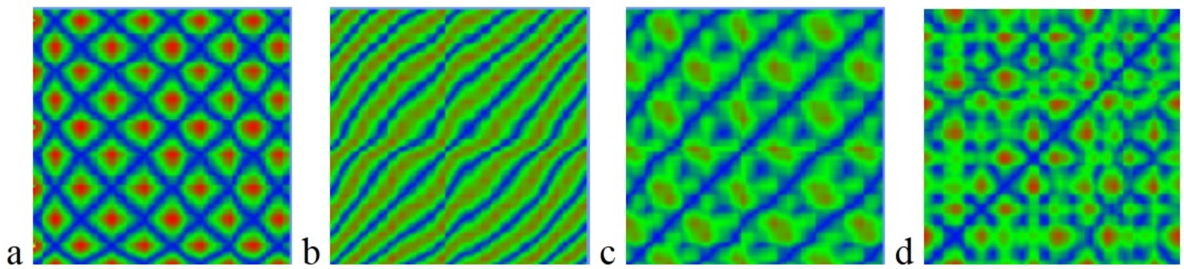


Figure 3.6: TT plot examples from Imfeld (2000). Generated from artificial movement data. a)line; b)circle; c)8-shaped; d)star. The color scheme ranges from blue ($\delta = 0$) to red ($\delta = max$) (Reprinted by permission from Dr. Stephen Imfeld, copyright 2000)

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3.4 Toolbox Development

In the end, we integrate all the modules above into a ArcGIS toolbox to create a flexible movement data analysis environment within a GIS framework. The ArcObject for .Net and Python are used as the programming languages. The Visual Studio 2010 is the development platform. To achieve better user-friendly interface and better graphics, the WPF engine is used to build the applications.

To better handle large dataset, the toolbox design sticks to information seeking mantra proposed by Shneiderman (1996): "Overview first, zoom and filter". As ArcGIS does well in data overview, zoom in or out and data query, the tools focus more on the graphical representation of filtered data. Interactivity is the most important feature in exploratory data analysis, so the toolbox try to give the users the flexibility to choose the attributes they are interested in and change the sliding window size or display modes whether they are using transparent pie or line connection.

Figure 3.7 is a general work flow chart of this paper.

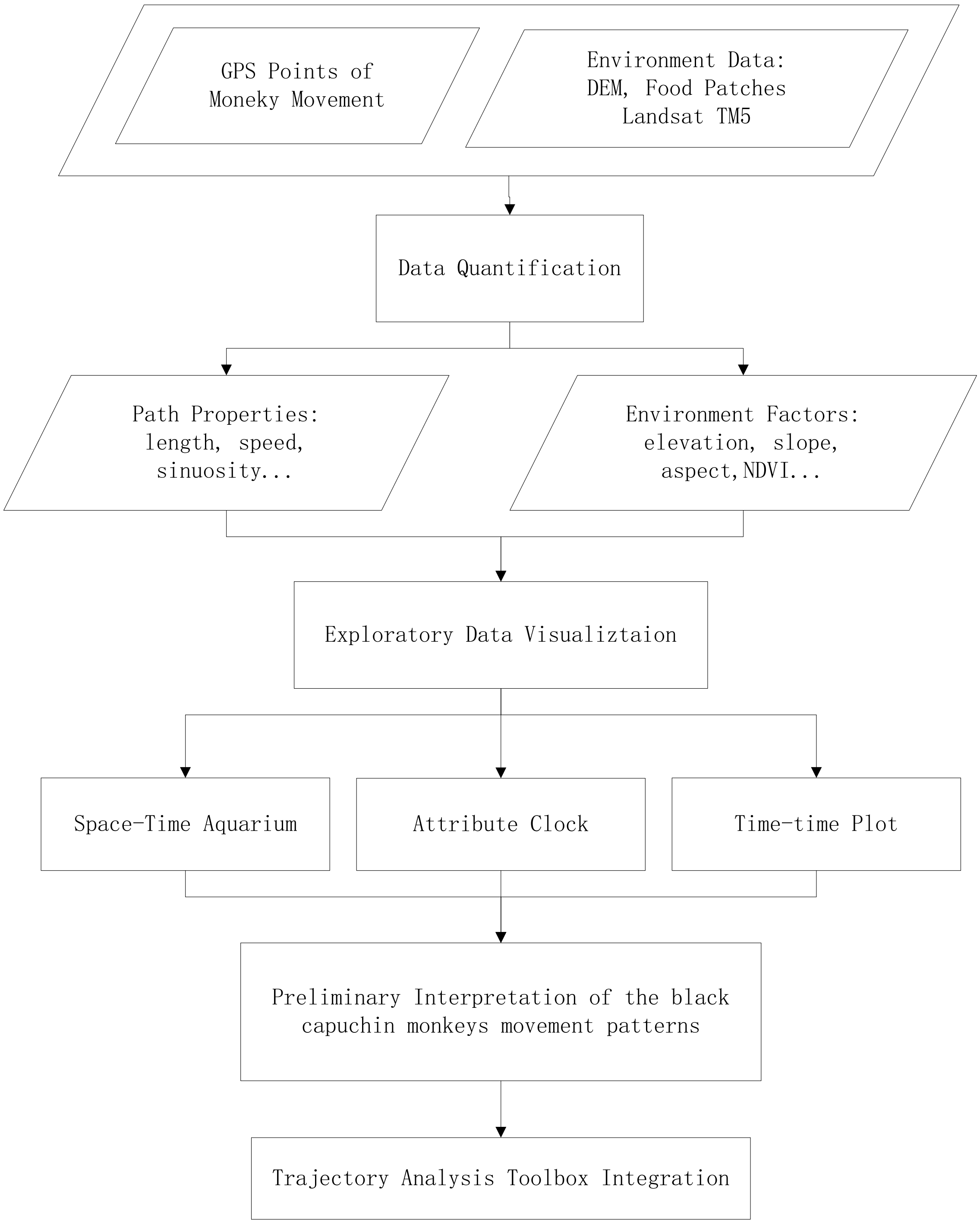

Figure 3.7: The general work flow chart of this paper, including data, path quantification, exploratory data visualization and toolbox integration

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Chapter 4

Results and Discussions

Methodologically, this project aims to tackle two major parts: 1) path quantification of movements and 2) visualization techniques to help the exploratory data analysis. With the "numbers" and exploratory data visualization tools, some findings of the black capuchin monkeys' movement patterns are presented below.

4.1 Path Quantification

The general path parameters includes S (space), T (time) and A (attribute). In the field data collection process, using the GPS, the spatial and temporal perspectives of the data movement are recorded as coordinates (x, y, z) and time stamps t. This project primarily focuses on the quantification on the attribute information. The A (attribute) includes both the external environment factors and internal path properties, which would be discussed separately below. To better understand the relationship between these numbers and the actual movement patterns of black capuchin monkeys, the movement data collected at food abundant month (April) and food scarce month (May) are compared.

4.1.1 Environment Variables

Considering the background environmental data we have, such as DEM, hydrology, fruit patches and Landsat TM5, and the potential factors that would influence the monkeys' movement strategy, we select several environmental variables: elevation, slope, aspect, NDVI (normalized difference vegetation index), distance to water and distance to the nearest food patches. For each movement point, all these variables are calculated and joined to point records in the attribute table. Some basic summary statistics are also calculated.

The slope and aspect of the study area are firstly derived from the DEM using the Spatial Analyst module in ArcGIS. The distance to the nearest fruit patch and water source of each point is calculated using *Euclidean distance* module. As there is almost no fruit in May, so the "distance to fruit patch" variable is only calculated for April. The Monkeys' movement points are displayed on the top of slope (Figure 4.2), aspect (Figure 4.3), distance to water (Figure 4.4) and distance to food (Figure 4.5). Then the values of these environment factors are assigned to the corresponding movement points using Extract Multi Values to Points module. Now the data includes the spatial coordinates (x, y, z), time stamps (t) and the above environmental attributes. The figure 4.6, 4.8, 4.9 are the histogram (or windrose diagram) of the environmental variables in April and May. All the plots are generated using R statistics software. From the plots we can get a general idea of the black capuchin monkeys' moving behavior. The comparison between April and May enable us to explore how the food, which is often considered to be the most significant factor, will affect the monkeys' motion.

In order to more clearly examine the data, summary statistics of these variables are calculated (Table 4.1). During the data collection period, the objective black capuchin monkeys' movement ranges around 800 meters elevation. And they are more likely to stay in relatively flat area (low slope) and not too far away from the water sources. At the aggregated month level, there is no obvious movement pattern variation between April and May, which is not that reasonable according to empirical study. Therefore, in-path dynamics of the environmental variables will be discussed in the exploratory data visualization.

Table 4.1: Summary statistics of the environmental variables in April and May. The * means "the distance to". The unit of slope, distance to water source and distance to fruit patch is meter, and the aspect is degree.

	April				May		
Summary	elevation	slope	water*	fruit*	elevation	slope	water*
Mean	807.50	9.95	8.87	115.64	806.64	10.57	16.46
Standard Deviation	17.56	7.70	8.53	73.06	15.40	6.37	6.73
Coefficient of Variation	0.02	0.77	0.96	0.63	0.02	0.60	0.41

4.1.2 Path Variables

The initial product of GPS data collection is a series of points. So in order to analyze the path properties, the points are connected to lines on daily basis. The variables selected to depict the path include path length, mean speed and turning angles.

As the black capuchin monkey follows a general temporal pattern: wake up in the morning and sleep in the near evening, so the descriptive variables are calculated at daily level. In this project, we have 11 days' movement data both in April and May. However, there are missing points in some days, either because of the bad weather or high activeness of monkeys. To get a more representative depiction of the paths, the days with over one hour's missing points are removed. In the end, we got 9 days' movement data for both April and May.

The daily movement length l can be easily computed by the sum of all the steps. And the speed v can be calculated either with the movement length l divided by the daily time range t_{all} or actual movement time t_{actual} (excluding all the stop times). Because the sinuosity is one of the most important descriptor of monkeys' moving strategy, several variables are used to get a comprehensive view. First we used the reverse straightness index, which is the ratio between the path length l_{path} and beeline distance l_{bee}. Also, the fractal dimension of

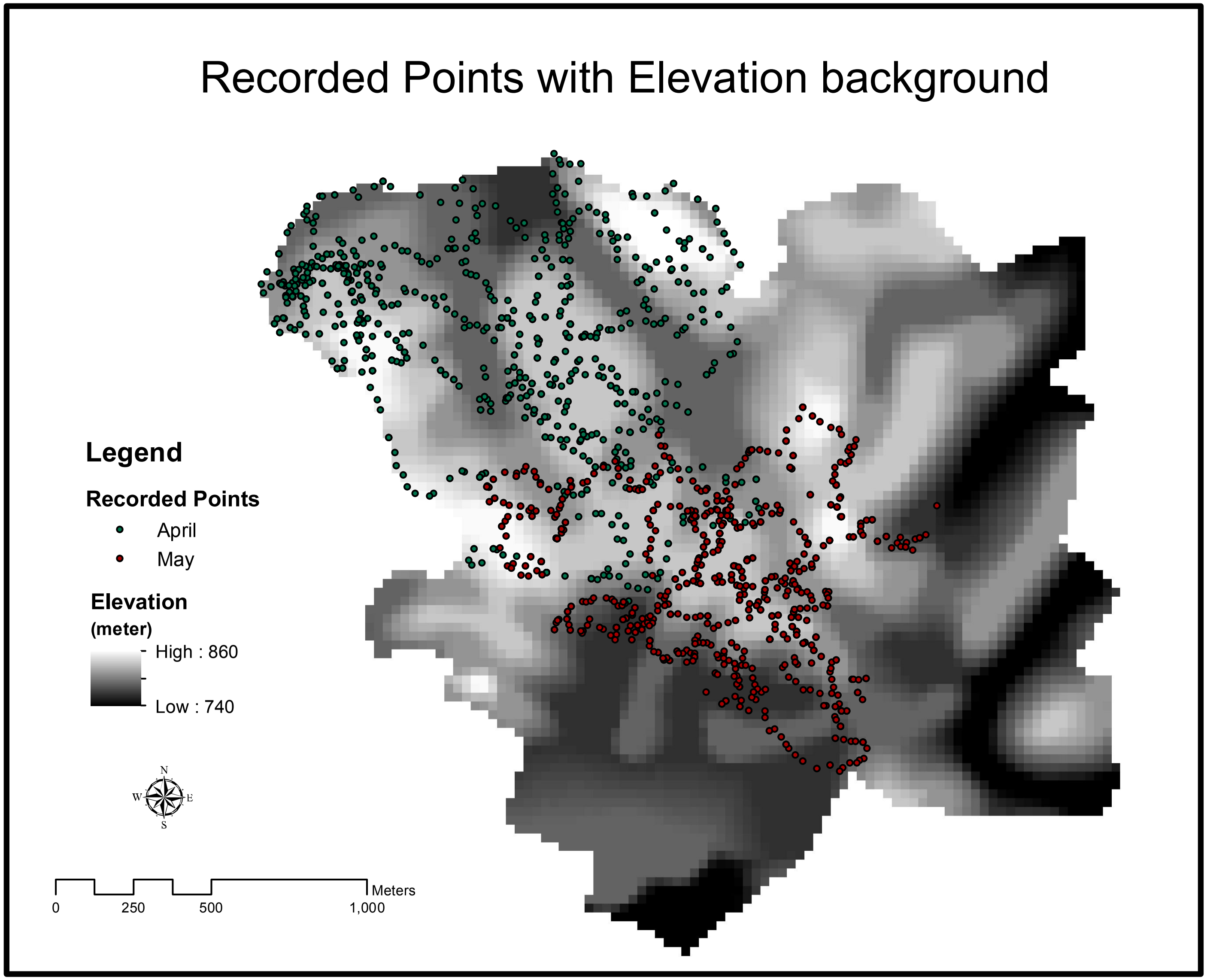


Figure 4.1: The DEM of the study area and the recorded GPS points

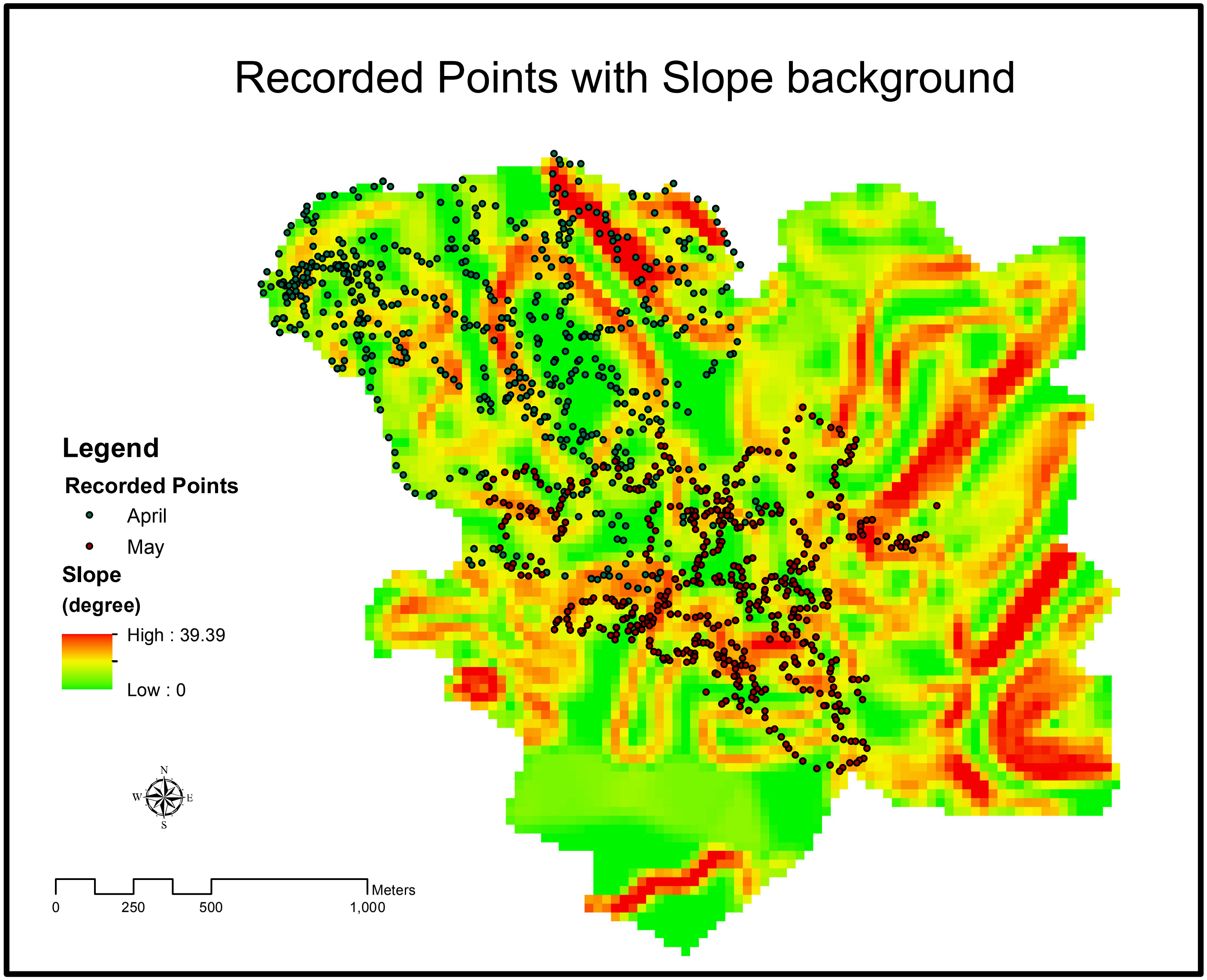


Figure 4.2: The slope of the study area and the recorded GPS points

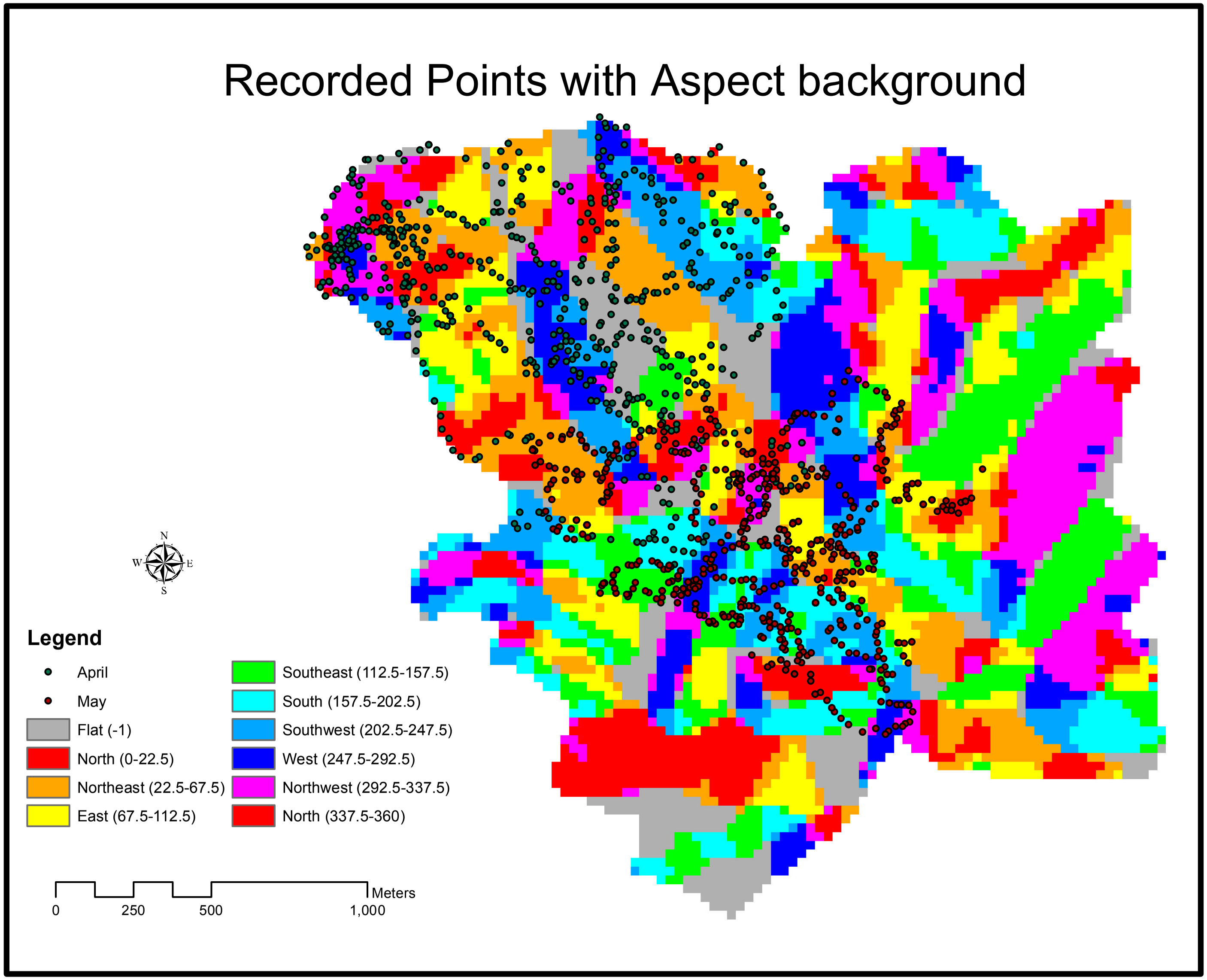


Figure 4.3: The aspect of the study area and the recorded GPS points

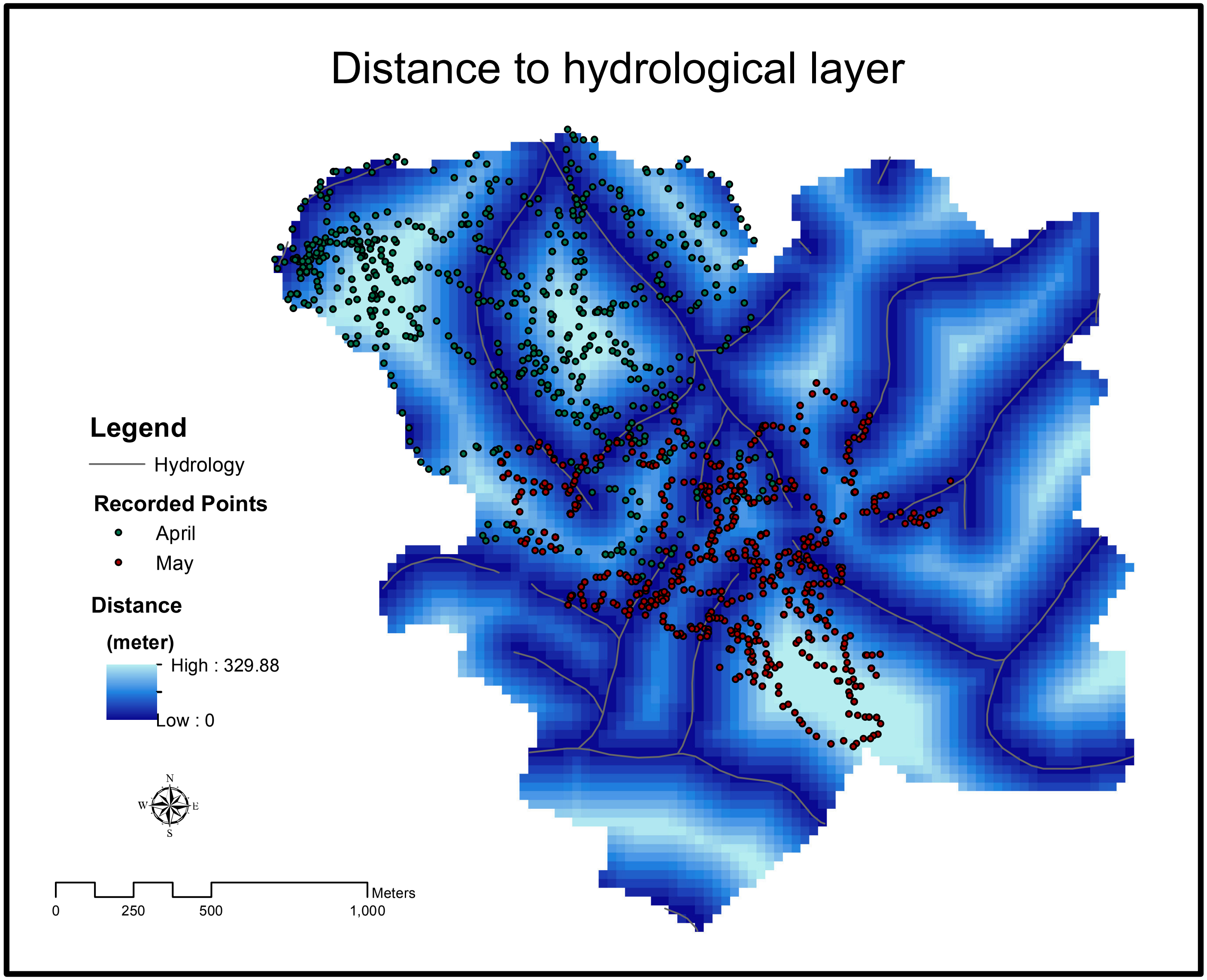


Figure 4.4: The distance to the nearest water sources and the recorded GPS points

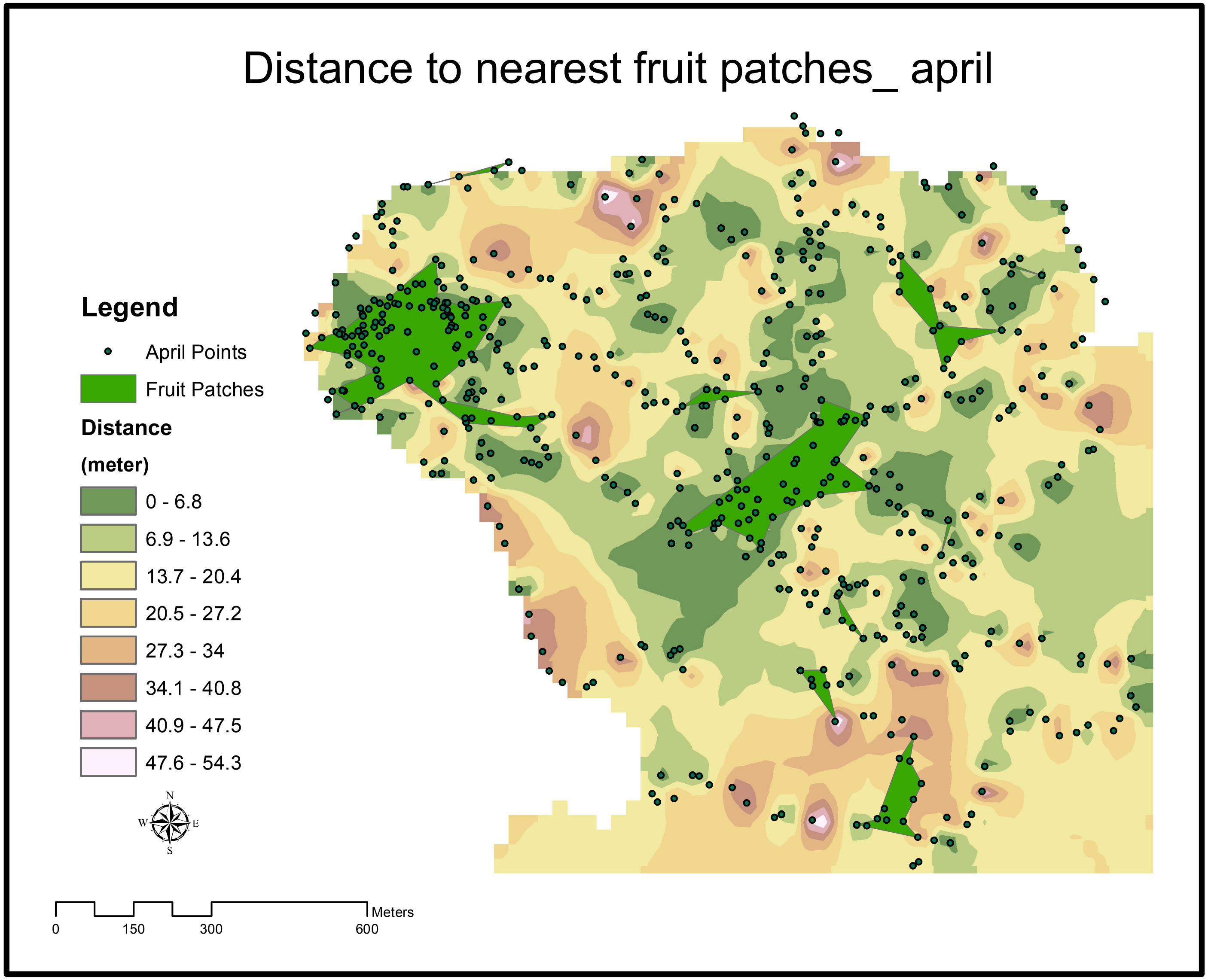


Figure 4.5: Fruit patches and the IDW Interpolation of the distance to the nearest food patches, and the recorded GPS points

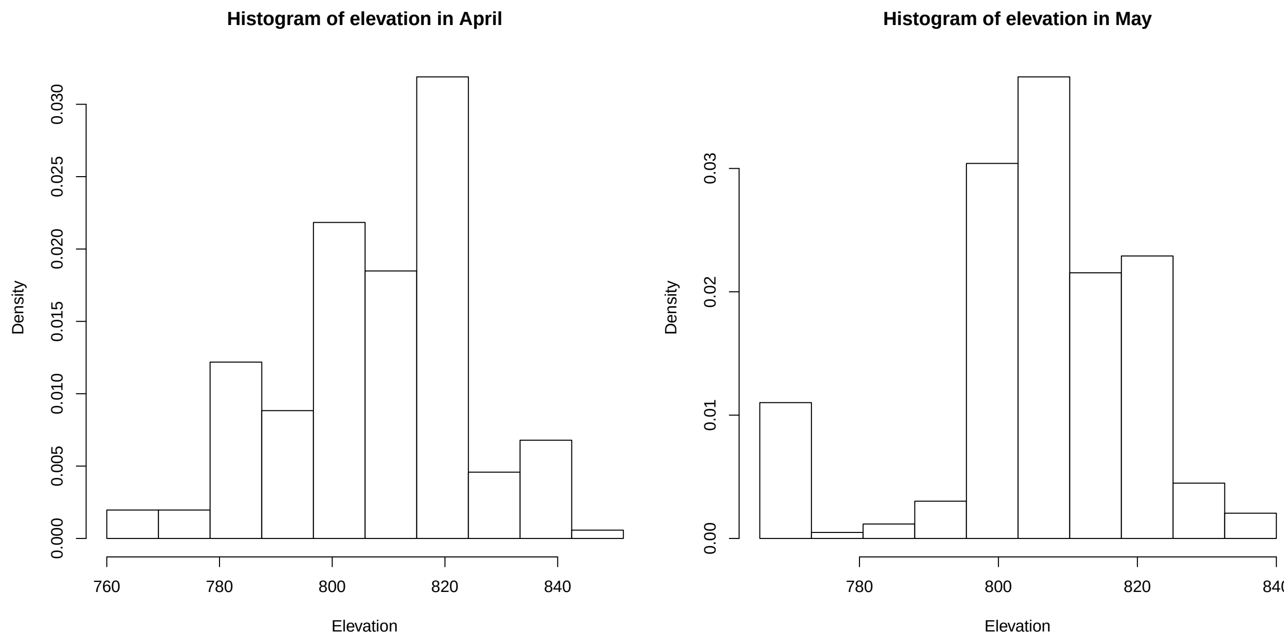


Figure 4.6: Histograms of elevation of the collected movement points (meter) in April and May

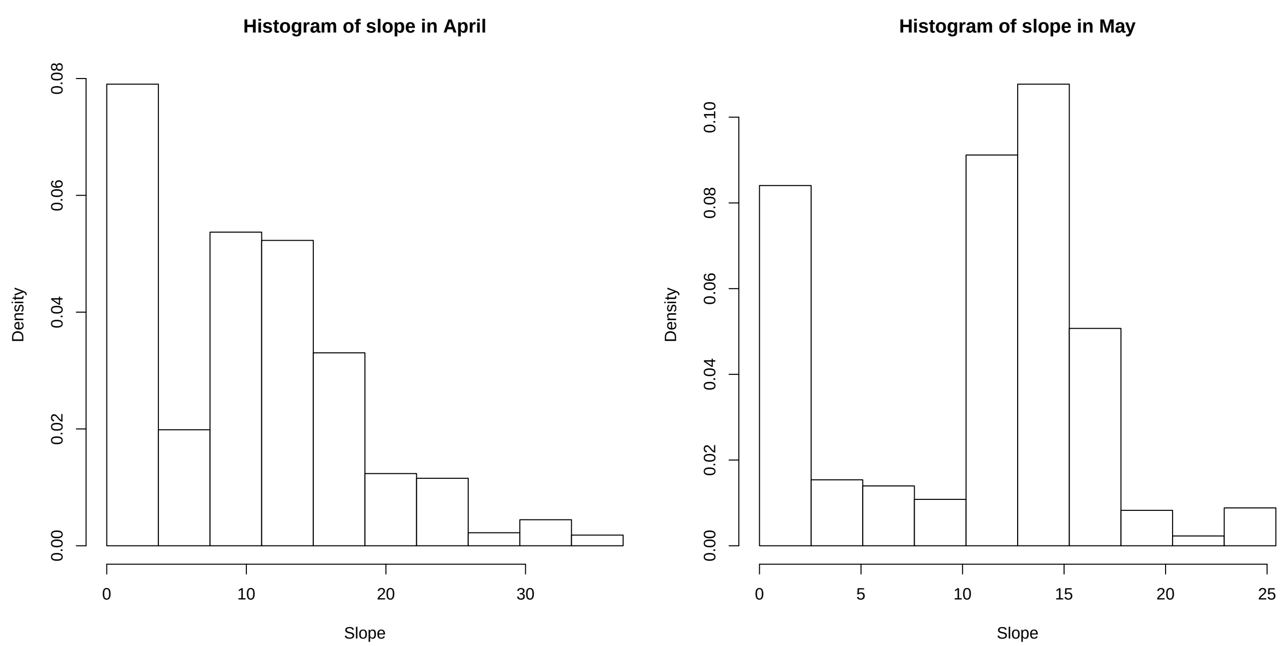


Figure 4.7: Histograms of slope of the collected movement points (degree) in April and May

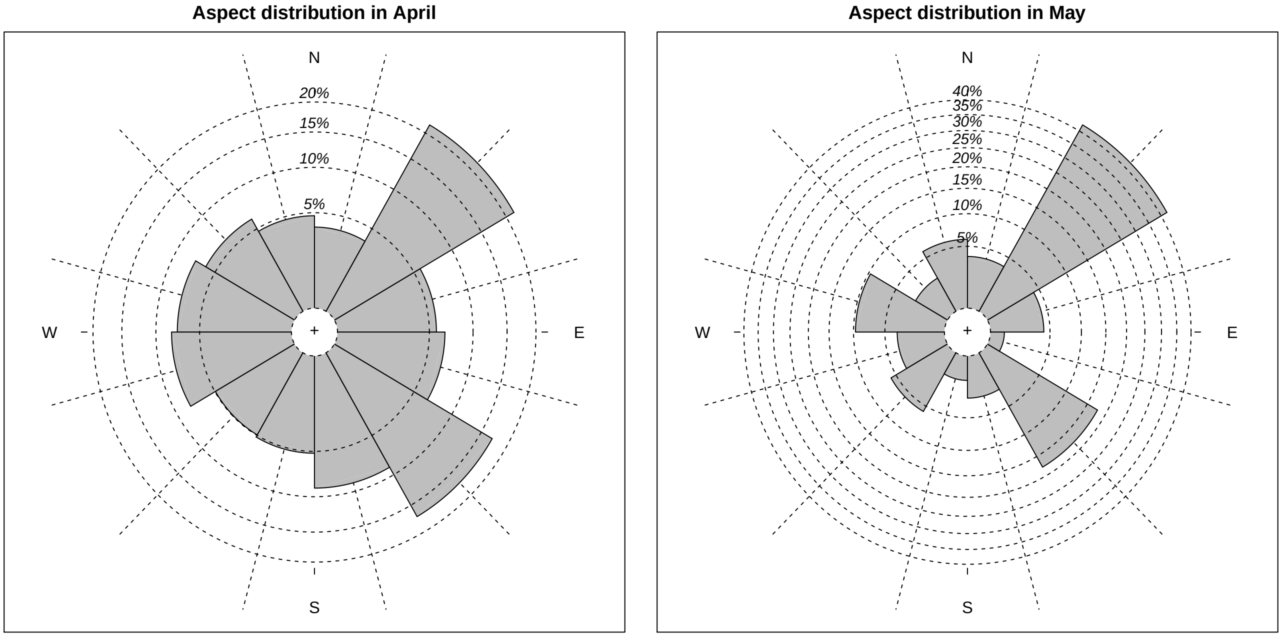


Figure 4.8: Windrose plots of slope of the collected movement points (degree) in April and May

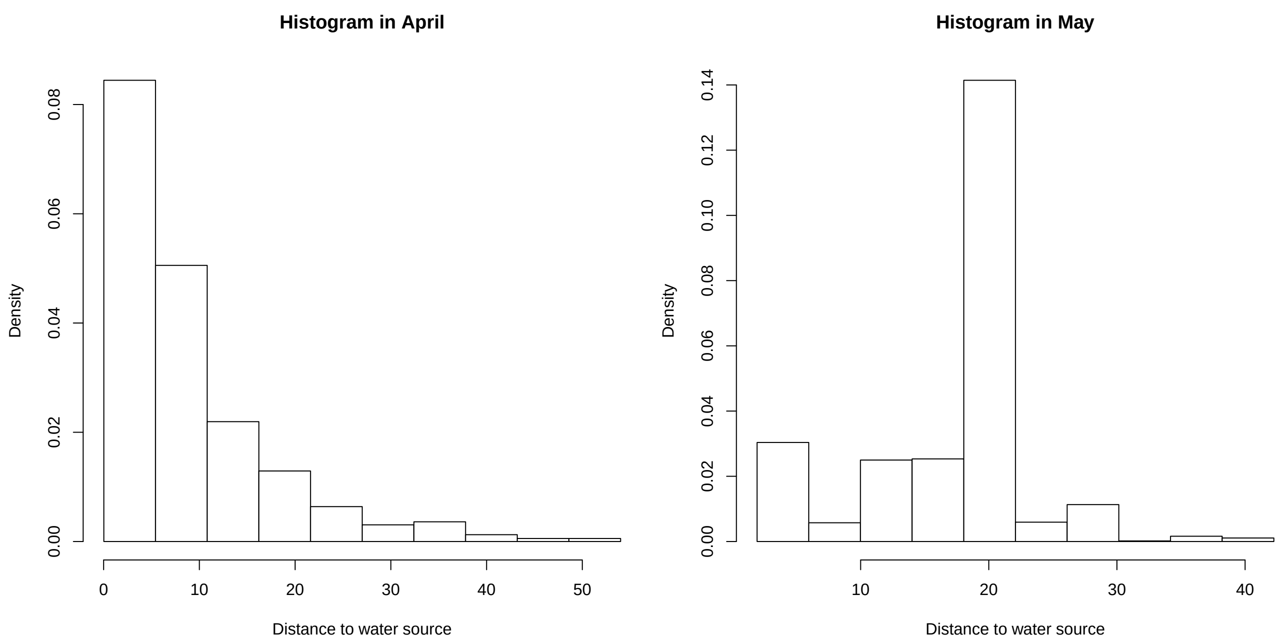


Figure 4.9: Histograms of distance to water source of the collected movement points (meter) in April and May

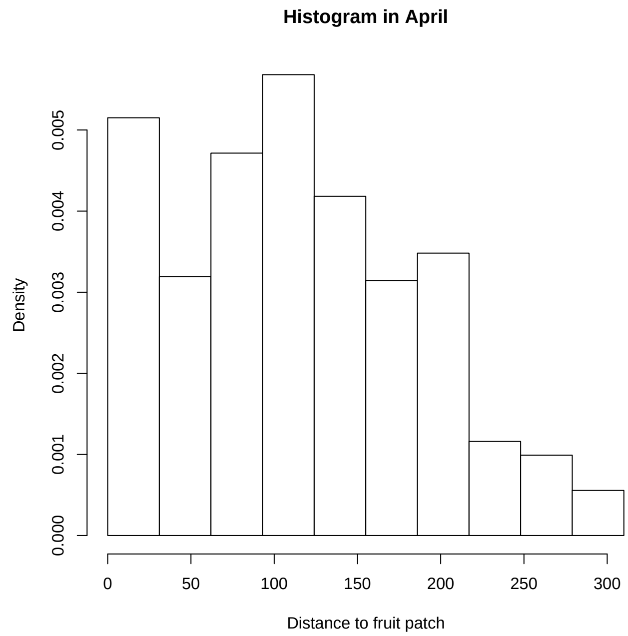


Figure 4.10: Histograms of distance to fruit patch of the collected movement points (meter) in April

each trajectory is calculated using the Hawths Analysis Tools for ArcGIS. The distribution of the turning angles are described with circular statistical variable: mean vector length. To actually place the numbers in an environment context, those path properties between April and May are compared using two-sample t test.

Computed path variables of the movement paths are summarized for April (Table 4.2) and May (Table 4.3). In order to more visually interpret the data, the bar plot of each variables are generated (Figure 4.11).

From the tables and plots, some general movement behaviors of the monkeys can be inferred. The daily movement length of the study group of black capuchin monkeys ranges from 1000 to 4000 meters. They usually travel at an average speed of 6 meters per minute. The distribution of the movement points follow a general decline trend as the “slope”, “distance to water", and "distance to food" increase, which means that the monkeys are more likely to stay at low energy-consuming area, and keep appropriate distances from water and fruit patches. There is an aspect "peak": northeast, for both the aspect windroses in April and May. The reason for this might be that northeast aspect is warmer and gets more sunshine. Differences exist between April (food-abundant month) and May (food-scarce month). For example, the daily movement length and the traveling speed in April are notably larger than May. This implies that with sufficient food sources, black capuchin monkeys are more energetic. Besides, from the reverse straightness index and fractal dimension, we can know that the paths are more sinuous in April than in May. This can also be inferred from the distribution of turning angles descriptor: mean vector length, which ranges from 0(uniform, fully dispersed distribution) and 1(punctual distribution, all angles being equal). For the data in this project, the mean vector length of the paths in April is visually smaller than those in May. This might imply that the black capuchin monkeys are more likely to choose random walk moving strategy during food abundant season.

Most of the "visual" interpreted results coincide with previous studies of black capuchin monkeys. To make it more convincing, the two-sample t test is applied to compare those variables between April and May (Table 4.4). The only statisticaly different variable is the average daily moving length in April is longer than the moving length in May. The combination of moving strategies within one day makes it hard to detect the potential movement patterns. Therefore, it is necessary to examine the path at small scales and to explore the in-path dynamics of the variables, which will be done in exploratory data visualization.

4.2 Exploratory Data Visualization

From the above environmental variables and path properties, we can get a general view of the study group of black capuchin monkeys' ranging strategies and behavior patterns. However,

Table 4.2: Path properties of April. The speed here is calculated as the path length divided by the actual travel time.

Day	Length(m)	Speed(m/min)	Sinuosity	Fractal Dimension	Mean Vector Length
11-Apr	1795.0	9.45	2.30	1.30	0.35
12-Apr	2425.1	10.10	5.04	1.72	0.25
14-Apr	2308.2	3.95	5.46	1.55	0.26
15-Apr	3138.1	7.21	6.57	1.73	0.12
16-Apr	3029.5	8.19	6.75	1.80	0.22
17-Apr	3872.6	8.15	11.27	2.14	0.10
18-Apr	2716.1	7.05	6.63	1.77	0.24
19-Apr	2242.1	7.60	4.40	1.57	0.26
20-Apr	2696.1	7.81	5.30	1.65	0.14

Table 4.3: Path properties of May. The speed here is calculated as the path length divided by the actual travel time.

Day	Length(m)	Speed(m/min)	Sinuosity	Fractal Dimension	Mean Vector Length
10-May	1112.5	5.56	2.30	1.29	0.47
11-May	1202.5	5.23	2.51	1.32	0.34
12-May	1391.7	6.33	3.70	1.53	0.24
14-May	1533.9	5.68	4.06	1.54	0.23
15-May	1999.5	5.63	8.48	2.00	0.13
16-May	2105.7	6.38	3.70	1.45	0.20
17-May	1854.2	5.15	3.64	1.43	0.22
18-May	1357.5	4.52	4.96	1.64	0.14
19-May	1026.1	5.40	2.45	1.32	0.34

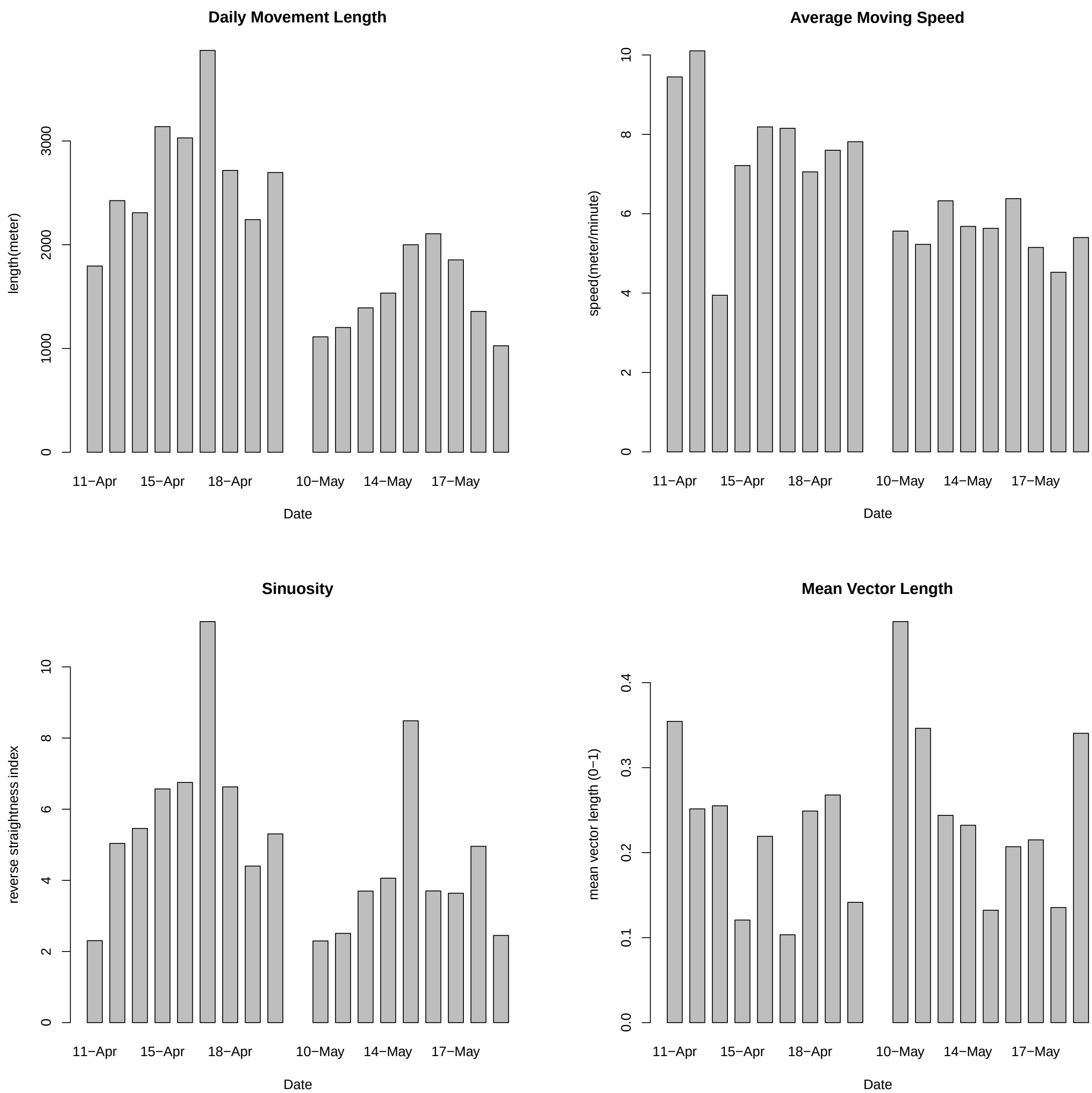


Figure 4.11: The daily path properties: Daily movement length, Average moving speed, Sinuosity and Mean vector length in April and May

Table 4.4: Two-sample t test between path properties in April and May

Null Hypothesis	p-value	Result
April Length < May Length	0.0001	reject
April Sinuosity < May Sinuosity	0.533	non-reject
April MVL > May MVL	0.094	non-rejct

as the environmental conditions changes all the time, the monkeys' internal decision-making of 'where to go' also vary. Therefore, the computed descriptors at multiple scales may lead to completely different results. In this study, we applied exploratory data analysis to address this problem by exploring in-path variables within dynamic time window. Considering the nature of geographic data, the visualization techniques play the major role in the data exploration process. Three exploratory data visualization methods are used in this study: space-time aquarium, attribute clock and time time plot.

4.2.1 Space-time Aquarium

With the x-y plane to represent space and an additional z axis as time, the space-time aquarium provides a good solution to integrate both the spatial and temporal components in one graphic, which is particularly important for movement data. In order to make it fully compatible with GIS data, the space-time aquarium is developed in ArcScene.

Figure 4.12 is a screen capture of the space-time aquarium of the moving paths from a perspective view. The bottom layer is the DEM, and each horizontal surface represents the time stamp at three hours' interval, from 6:00 am to 6:00 pm. And each polyline represents the objective group of black capuchin monkeys' daily path. The colored points along the path show the monkeys' activity patterns; green means eating while red means non-eating. Also the geometry characteristics of the polyline imply the path properties. For example, a vertical line segment corresponds to the stop period. For other line segments, the steeper slope corresponds to the faster the movements speed.

In ArcScene, user can have the flexibility to zoom in, zoom our and rotate the 3D cube and view space-time aquarium from different angles. For instance, seen from orthographic view, the space-time aquarium is an overview of spatial distribution of moving trajectories (Figure 4.13).

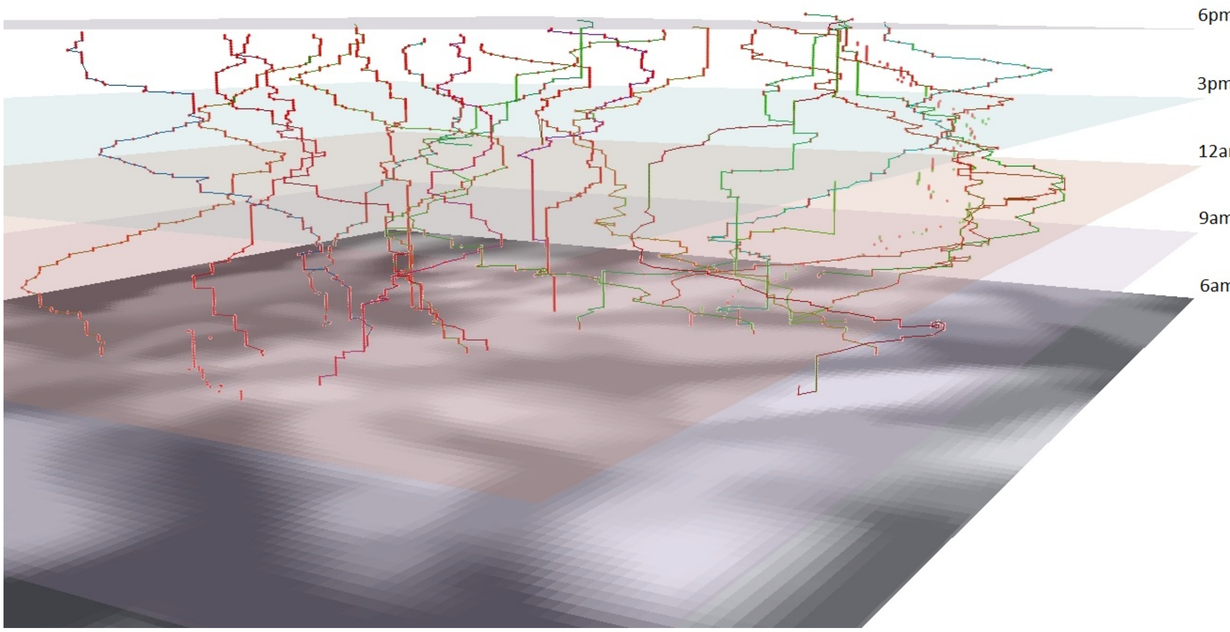


Figure 4.12: Screen capture of space-time aquarium of the movement trajectories of the black capuchin monkeys in April and May

In order to give the users more interactions with the data, a temporal data query module is added to the space time aquarium representation. Users can select the time period they are interested in and the movement points and path segments will be filtered. This help users to focus on the time ranges of interest. For example, according to field work experience of Dr Andrea Presotto, the monkeys have an interesting sleeping site selection habit, that they never sleep within the fruit patches. In other words, after they eat some fruits and want to go to sleep, they would travel a certain distance away from the fruit patch. Figure 4.14 filters the movement points and trajectories within 3:00 pm to 7:00 pm time frame. After each green vertical line usually follows a displacement over x-y plane, which coincides with the pre-knowledge. In this way, the space-time aquarium and the temporal query function combined help us identified many hidden spatio-temporal movement patterns.

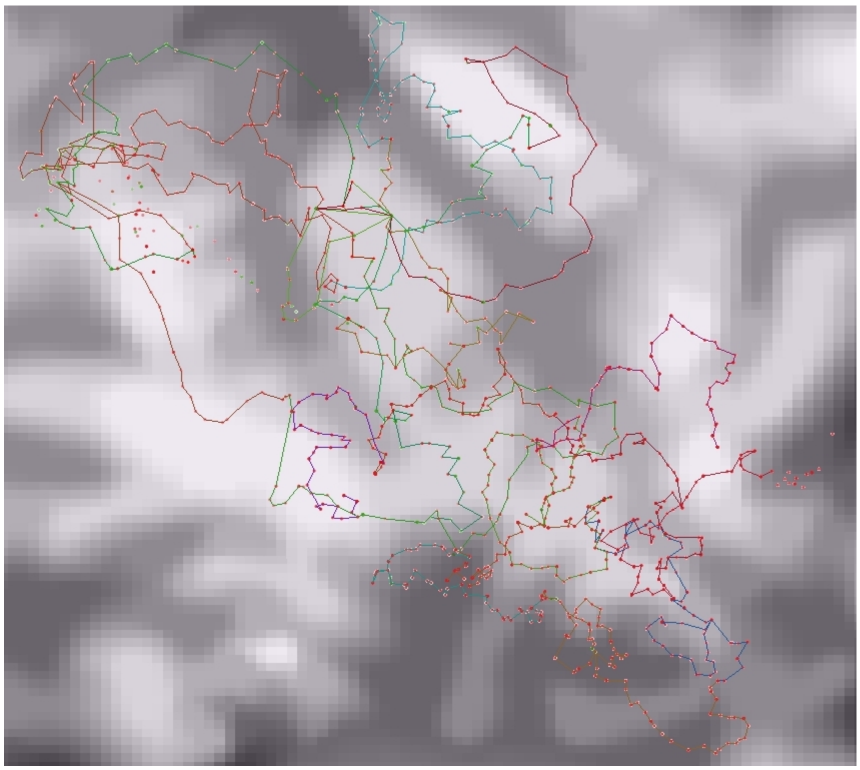


Figure 4.13: Orthographic view of the space-time aquarium

4.2.2 Attribute Clock

Most of the current GIS software packages are good at spatial data analysis, yet weak at temporal perspective. And for the movement data, the time is actually an essential part. Therefore, this study focuses on the temporal dynamics along the trajectories. In this sense, the attribute clock provides a good solution for temporal data representation by projecting the movement points to a virtual clock.

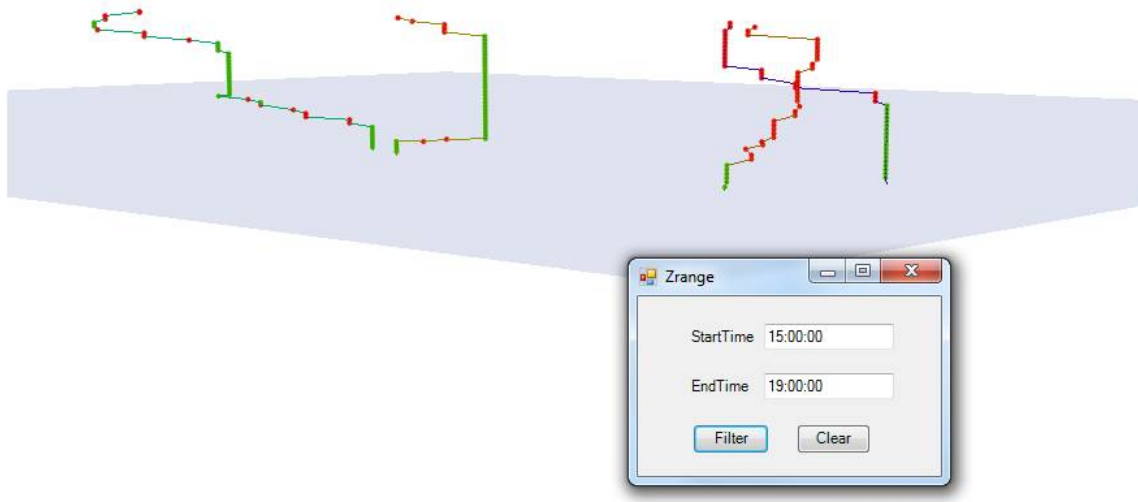


Figure 4.14: Filtered space-time path from 3:00pm to 7:00pm, the sleep site selection pattern is identified

The attribute clock is integrated into ArcMap as a trajectory analysis add-in (Figure 4.15). The right side displays the virtual clock, which ranges from 6:00 am to 6:00 pm. Different angles represent different time stamps. For any variable projected to the attribute clock, the origin point represents its the minimal value and the outmost ring is the maximum value. All the other points are scaled within the origin point and outmost ring. Then similar to space-time aquarium, all the points are connected to polylines along the time. For the data input section, users can choose any pre-loaded layers in ArcMap. Also, users are required to select the time field and the variable they want to explore. Figure 4.16 is an attribute clock example showing the elevation changes in April 12th. The elevation in that day ranges from 779 meters and 840 meters. The green and red points separately represent the eating and non-eating activities of the black capuchin monkeys. In order to more clearly present the daily activity pattern, an extra outbound ring is added to the attribute clock. For better user experience and more interactions with the data, the tooltip is used, which can also be seen in Figure 4.16, so that the value of the corresponding point will show up on hover.

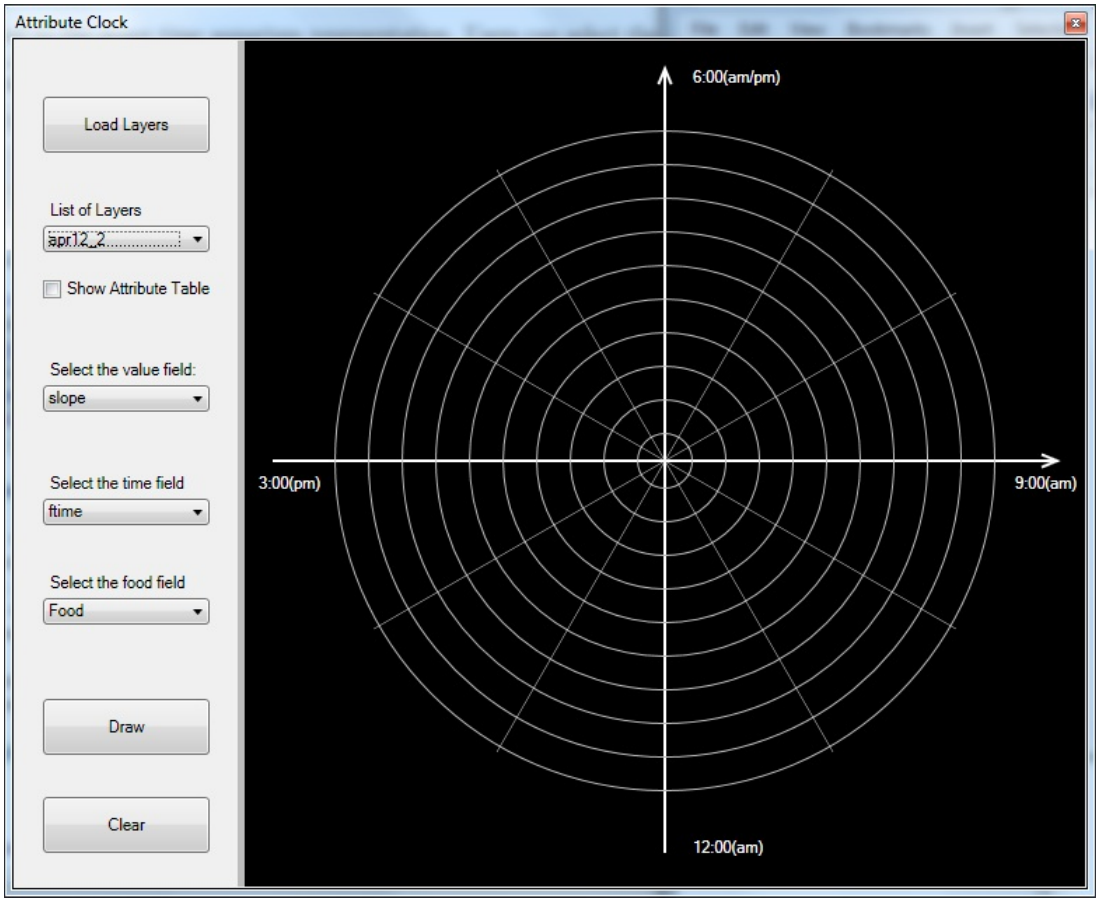


Figure 4.15: Attribute clock user interface

The monkeys stop frequently, either eat food or play with each other. Hence some variables, such as speed, are not continues at temporal domain. If we still connected the points to polylines, we could get really poor visualization (Figure 4.17). To solve this problem, the transparent pie technique is developed. The basic idea of the transparent pie is that instead of connecting the 0 value points with lines, the stop time periods will be filled with transparent pies. In this way, the temporal continuity of the variables dynamics can be kept. Besides, the stop periods, which are particularly important for animal behavior study, will be highly emphasized in the data representation. The Figure 4.18 is an example of the transparent pie representation of the monkeys' speed dynamics in April 12th. From the graphic,

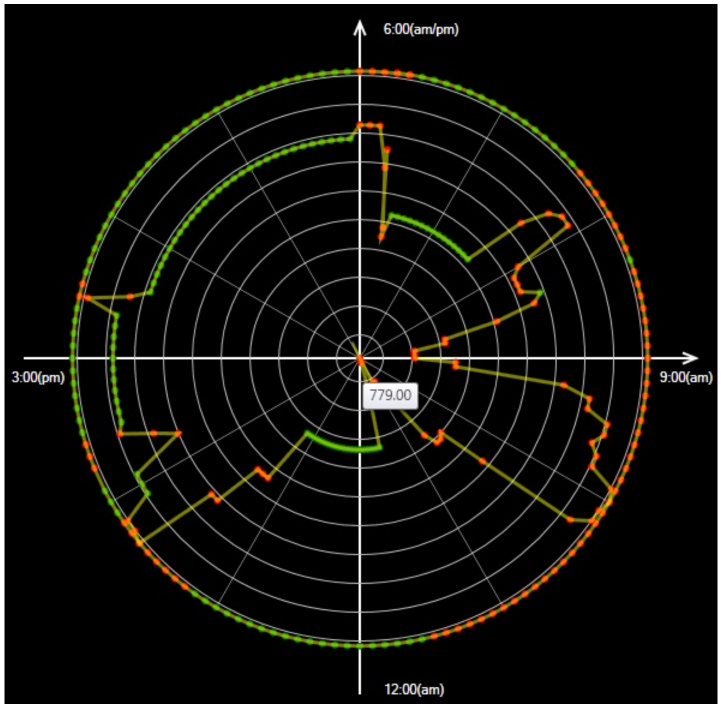


Figure 4.16: The attribute clock of the elevation dynamics in April 12th

we can easily see during what periods do they stop, how long do they stay there, what is the purpose of the stay: eating or non-eating?

Another advantage of using the *transparent pie* is that by controlling the transparency of the "pies", we can overlay several days' movement data together to examine the aggregated properties of the "stops". Figure 4.19 is an example of transparent pie overlay of the monkeys' movement in three days. The lower the transparency, the less "stop" during that period of time. Some general activity patterns can be seen (Figure 4.19). For example, the monkeys rarely stop during 8:00 am and 9:00 am, but often stop in the pre-evening. The potential explanations could be that after they wake up, they are highly energetic and keep moving to find new food sources, and before they go to sleep, they usually stop to eat some food. Though the visual interpretations can not be regarded as definite conclusions, at least they can be lead to new questions and potential solutions, which is a major goal of exploratory

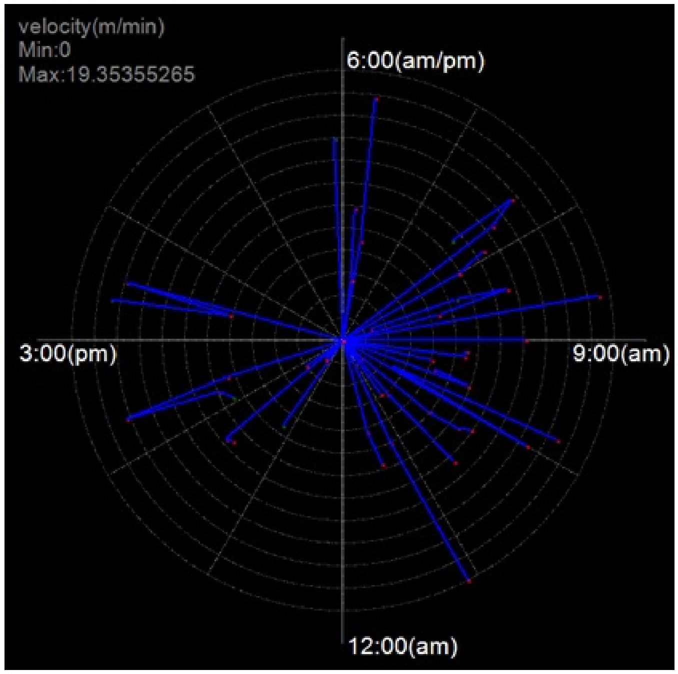


Figure 4.17: Bad visualization example of the monkeys' speed dynamics in April 12th

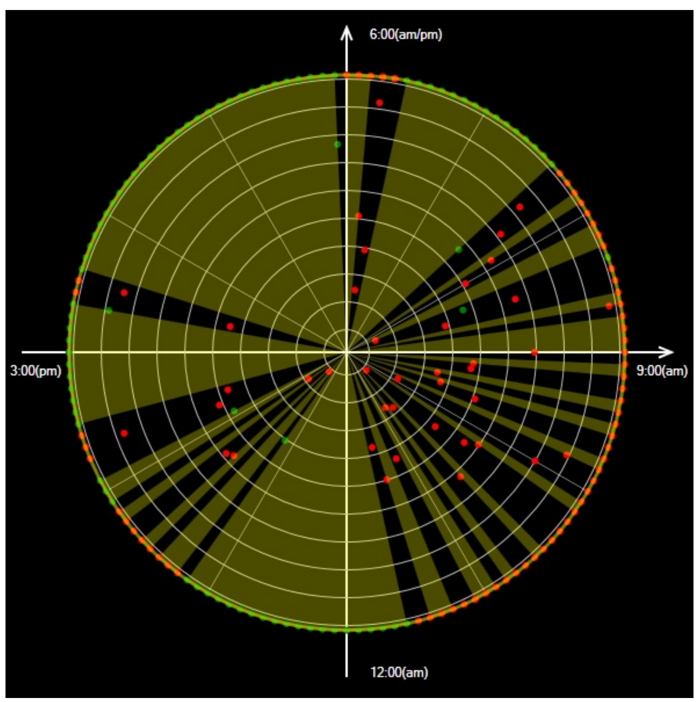


Figure 4.18: Transparent pie example of the monkeys' speed dynamics in April 12th

data analysis (EDA).

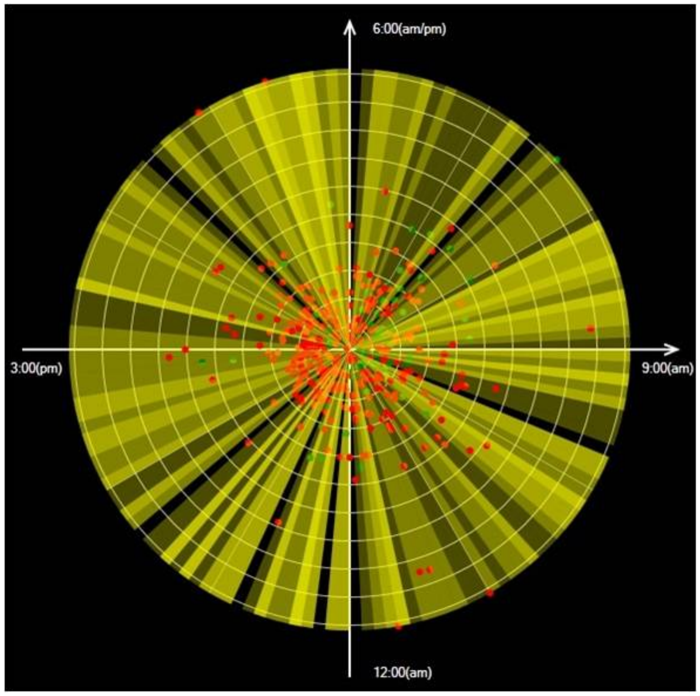


Figure 4.19: Transparent pie overlay example of the monkeys' speed dynamics using three days' movement data

4.2.3 Time-time plot

Another temporal dynamics visualization technique developed is time-time Plots, which contains two time axes to examine the intra-dataset parameters. As the distance(s) is the most important intra-dataset spatial parameter, TT-δ plots are generated to analyze the potential spatio-temporal patterns of the black capuchin monkeys' movement.

The two time axes both range from 6:00 am to 6:00 pm. They are then scaled to numeric range from 0 to 360 to facilitate the data visualization. The value of each point (t_1,t_2) is the distance between location at t_1 and t_2. Because the distance from t_1 to t_2 is the same with the distance from t_2 to t_1, the result is a symmetric matrix, which leads unnecessary visual redundancy. So only the distance from t_1 to t_2 is calculated. To estimate the overall distance distribution in the time-time space, the interpolation technique is used to create a continuous surface. The color scheme "blue to red" is applied to the calculated distances, with blue representing the minimum value and red for the maximum value. In addition to the continuous surface, the contour line and 3D mesh representations are also developed. Users can choose different visualization methods or combine them in one graph. As can be seen from the user interface of time-time plot (Figure 4.20), users have the flexibility to use different chart types, and view the 3D meshes surface from different angles.

Figure 4.21 is a TT-δ plot example of the movement trajectory in April 16th with different chart types. To the right of each TT-δ is a color range scheme, which serves as a reference for the users to find out the corresponding value for each color. For the April 16th trajectory, the monkeys kept moving away from their sleeping site until around 11:30 am, when they reach the farthest point (around 1000 meters). And then they started to move back and stop around 300 meters from the previous sleeping site. There are many horizontal or vertical lines in the plot, which are especially obvious in the contour representation. Those linear lines correspond to the stop periods of the monkeys' moving trajectory.

Two typical trajectories in April and May are compared (Figure 4.22). In April, the monkeys are more likely to follow the random search pattern and in May, they usually make oriented paths. The TT-δ plots also prove that by revealing two completely different patterns. There are more red spots in April TT-δ plot, which indicates the paths are much more sinuous. And one interesting thing found is that in the May TT-δ plot, there are many horizontal and vertical lines. In other words, the monkeys stop more frequently in May, maybe due to the lack of energy. This also explains why the path length in May is much shorter than that in April.

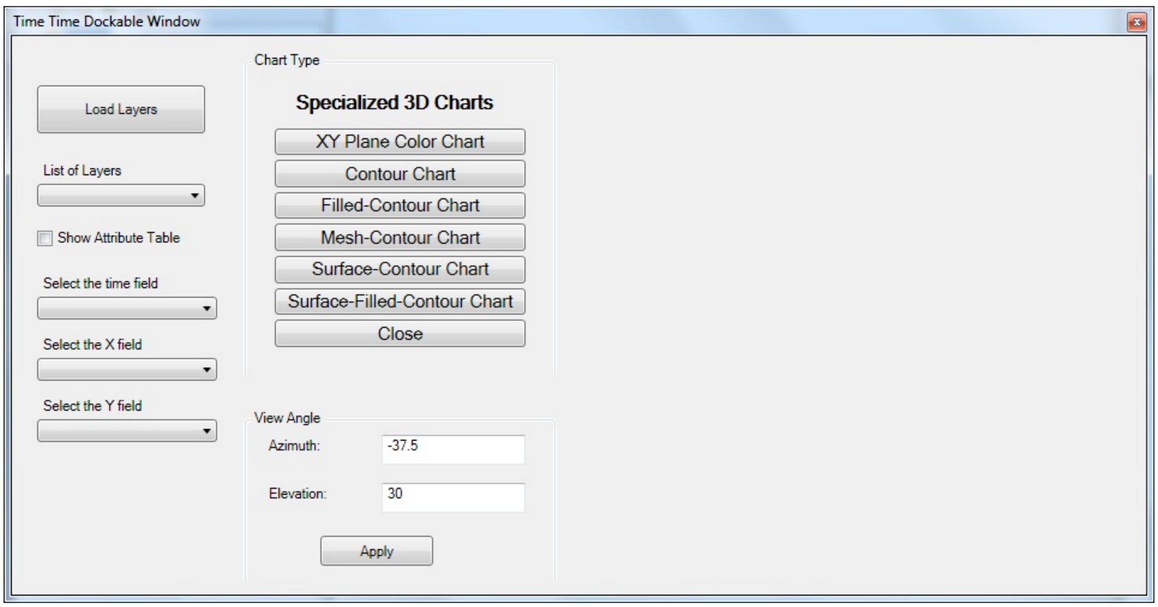


Figure 4.20: The user interface of T-T plot

4.3 Toolbox development

Finally, the space-time aquarium, attribute clock and time-time plot are integrated as a toolbox into ArcGIS to facilitate the future exploratory analysis of animals' movement data. The space-time aquarium is developed as a ArcTool module using Python; the attribute clock and time-time plot are developed with ArcObject for .Net. The users can select the spatial layer, time period and attribute with great flexibility. Then the spatial, time and

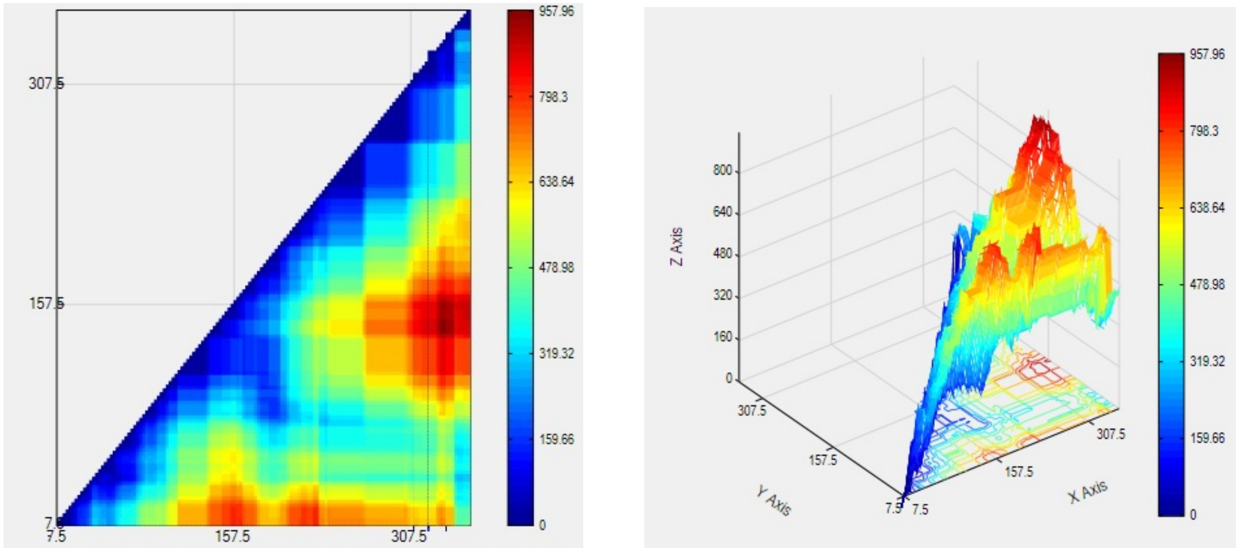


Figure 4.21: The $TT - \delta$ plot example of the movement points in April 16th. Left is continuous surface plot. Right combines the 3D mesh and contour lines.

attribute information can be presented with different exploratory visualization techniques.

For both the attribute clock and time-time plot, the time window technique is implemented. The various properties of the trajectories can be examined at different scales. Figures 4.23 and 4.24 are two examples of the the plots generated at two different temporal scales. In this way, users can interactively explore movement data.

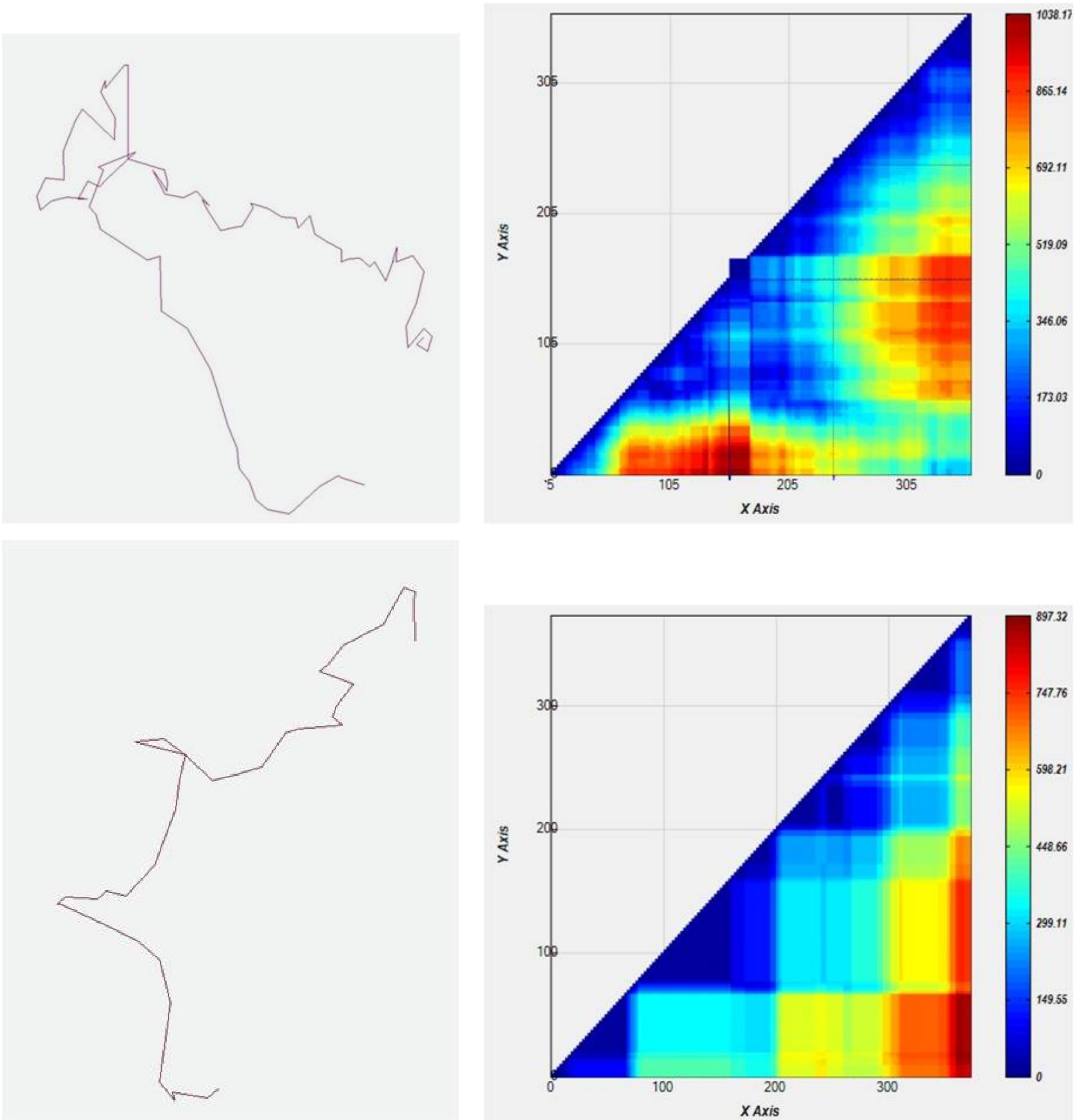
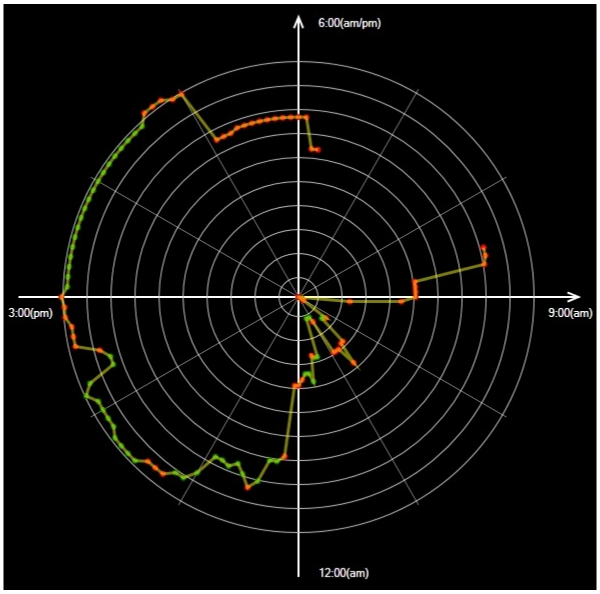


Figure 4.22: Comparison between the random walk path and oriented path. The first row are the random search path and its TT-δ plot, and the second row are the oriented path and its TT-δ plot.



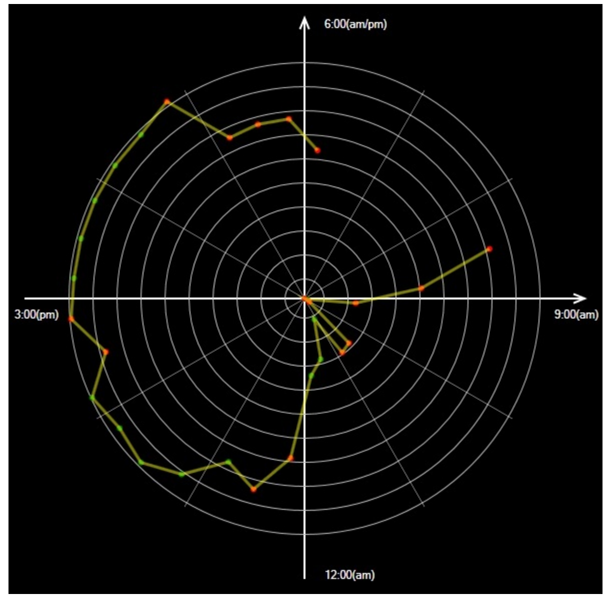
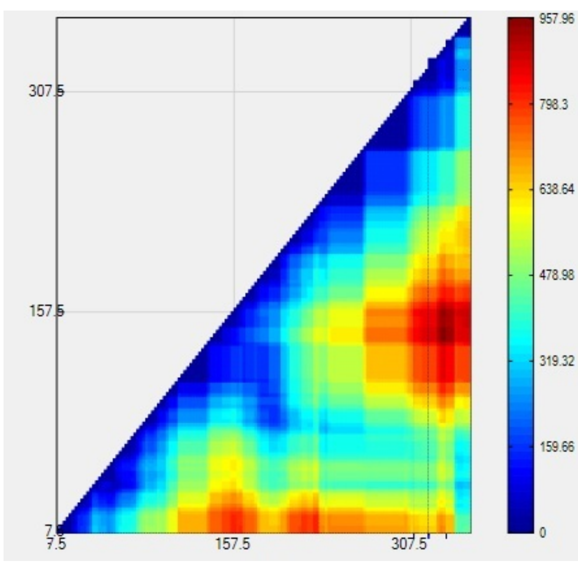


Figure 4.23: The elevation clock of April 14th at two time scales. Left is the elevation clock at 5 minute interval. Right is the elevation clock at 20 minute interval.



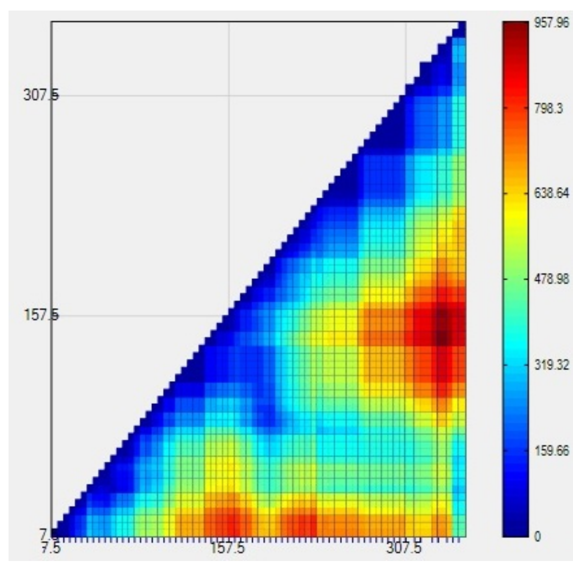


Figure 4.24: The TT-δ plots of April 16th generated at two different time windows. Left is the TT-δ plot at 5 minute interval. Right combines the TT-δ plot at 10 minute interval.

Chapter 5

Conclusion

The black capuchin monkeys' movement has been studied from various perspectives. For example, psychologists focus more on the spatial cognition or navigation strategy of the monkeys; primatologists are interested in the taxonomy of monkeys and how different species vary in the activity patterns. As geographers, we focus on two most important components in geography: space and time. Therefore, tools to interactively explore and visually interpret movement data need to be flexible and take both spatial and temporal components into consideration.

5.1 Summary of Work

We summarize our work corresponding to the four research objectives.

Firstly, corresponding to the first objective proposed in Chapter 1, both the environment factors and path properties are computed at different temporal levels. With the quantify numbers and generated graphs (histograms and windrose plots), we get an overview of the monkeys' behavior patterns. This allows us to answer questions such as what are their mean daily traveling length, at what slope ranges do they most stay, do they have any preference over the aspects of the mountain.

Secondly, considering the complex structure of the movement data and the uncertainties of the monkeys' navigation strategies, we applied the exploratory data analysis (EDA) in the in-path variables analysis. Also because of the nature of the geographic data, the visualization techniques are primarily used in the EDA. Three visualization techniques are developed. The first one is the space-time aquarium, which represents the space coordinates in x-y plane and the time stamps along the z axis. The temporal query module is added that the users can select the time periods of interest and explore different variables dynamics. Because current GIS works well in spatial data analysis, this project aims more at data exploration functions at temporal domain. The second exploratory data visualization technique is the attribute clock. Its basic idea is to plot the movement points to a virtual clock. The angle represents the time stamp and the radius measures the value of the specific variable at the corresponding time stamp. To address the "variable discontinuity" issue, the transparent pie method is developed. For any of the monkeys stop time period, the corresponding angle range of the attribute clock will be filled with a pie. By controlling the transparency of the pie, the users can overlay several days' movement trajectories in one attribute clock and examine the most frequently stop periods. The third technique is the time-time plot, which has two time axes and a third dimension to represent the spatial information. In this project, we calculated the distance δ between t_1 and t_2 as the third dimension value, or so called TT-δ plot. By projecting 3D space-time data to a 2D image, the movement patterns can be more easily identified. The exploratory data visualization techniques above prove efficient in the space-time movement patterns analysis.

Thirdly, in order to put the computed numbers and generated graphs in a real world context, and further examine one of the most important factors: food distribution, we compared the movement trajectories in April (fruit-abundant month) and May (fruit-scarce month). Both visual interpretation of the graphs (histograms and windrose plots) and two-sample t test are used in the comparison. The results reveal that at daily level, the movement pattern differences do exists, yet are not statistically significant. Therefore, I went a step further to investigate in-path dynamics. From generated space-time aquarium, attribute clock, and TT-δ plot, we can clearly identified the movement differences under two different scenarios. Generally, the monkeys are more likely to adopt random search strategy during fruit abundant month, while during fruit-scarce month, they would try to save energy by traveling shorter distance and make more oriented paths. Although the results of visual interpretation can not be considered as definite conclusions, the geo-visualization helps users to find the underlying patterns and possibly leads to new hypothesis for the further analysis and modeling of the monkeys' movement.

Finally, all the functions are programmed with ArcObject for .Net and integrated into ArcGIS as different modules. Users could have the flexibility of choosing different time periods, time window or selecting the variables of interest. Interaction with the data is also highly emphasized in the design of the tools.

5.2 Future Work

While the goals of this study have been accomplished, there are a few caveats regarding the data accuracy and tool design need to be mentioned.

Firstly, data with higher accuracy and large sample sizes could greatly increase the results. The environmental background data used in this project are at rather coarse resolutions. For example, the DEM layer is 28×28 meters resolution and the landsat TM5 image is 30×30 meters. In other words, it takes the monkeys around four minutes to move across one "cell". Also, since the monkeys spend most of the time in the tall trees, the estimated elevation values from the DEM layer are not the actual "elevation" of the monkeys. The monkeys' movement can be categorized as small-scale movement, how the height the monkeys climbed on the trees really matters for their behavior study. For the fruit patches data we got in this project, only the fruit patches that the study group of monkeys have been to are recorded. So the variables "distance to fruit patches" can only be estimated as the distance to the fruit patches that the monkeys used, not the actual distribution of fruit patches. Without the accurate and complete environmental background data, it is impossible to model the relationship between the environmental factors and the monkeys' moving strategy. In addition, because the GPS collection of the monkeys' movement is really laborious and time-consuming, we only got ten days' movement points separately in April and May. However, the sample size is not large enough to run the statistical test. Especially for the data in this project, the uncertainty of the *sapajos nigritus'* movement greatly increases in dense forest. Larger sample size will help a lot in identifying the potential movement patterns.

Secondly, more interactivity features could be added to the exploratory data visualization tools developed in this project. Although the current tools are integrated in ArcGIS, the components are still independent. There is no communication between the attribute clock plots and ArcMap layers. In the future work, more linkages between space and time components will be developed. For example, if the users select the points in attribute clock, the corresponding points will be highlighted in the ArcMap window. Another problem is that the rendering speed of the graphs is relatively low in the ArcGIS dockable window. It takes over 10 seconds to rendering one day's TT-δ plot and crashes when three days' data are loaded. More efficient graphic tools need to be developed to fully users the flexibility to interactively explore the data.

Thirdly, the techniques have some inherent shortcomings. For example, the attribute clock works best with daily based data. For other temporal cycle, the "clock" might not be that intuitive. The TT-δ plot requires the movement data to be regularly collected at fine temporal resolution. Otherwise, the interpolation could result in serious bias for the no-data time period. In fact, during the field movement data collection, there are all different kinds of factors, such as the monkeys' high physical dexterity and dangerous animals, that would lead to the missing data.

To sum up, through the path quantification and exploratory data visualization, the black capuchin monkeys' movement patterns and their potential relationships with environmental factors are identified. The exploratory visualization techniques are integrated into a GIS toolbox. For the future work, more emphasis should be put on the modeling of animals' behavior. Environmental data with higher resolution and movement points with the actual elevation of the monkeys in the data collection could lead to significant improvement in the monkeys' movement models.

Bibliography

AbSaber, A. (2003). Os domnios de natureza no brasil: Potencialidades paisagsticas. *E. Ateli Editorial*. Cotia.

Amaral, P. J. S., Finotelo, L. F. M., De Oliveira, E. H. C., Pissinatti, A., Nagamachi, C. Y., & Pieczarka, J. C. (2008). Phylogenetic studies of the genus cebus (cebidae-primates) using chromosome painting and g-banding. *BMC Evolutionary Biology*, *8*(1), 169.

Andrienko, G., Andrienko, N., Bak, P., Bremm, S., Keim, D., von Landesberger, T., Plitz, C., & Schreck, T. (2010a). A framework for using self-organising maps to analyse spatio-temporal patterns, exemplified by analysis of mobile phone usage. *Journal of Location Based Services*, *4*(3-4), 200–221.

Andrienko, G., Andrienko, N., Bremm, S., Schreck, T., Von Landesberger, T., Bak, P., & Keim, D. (2010b). Space-in-time and time-in-space self-organizing maps for exploring spatiotemporal patterns. *Computer Graphics Forum*, *29*(3), 913–922.

Andrienko, N., & Andrienko, G. (2005). *Exploratory Analysis of Spatial and Temporal Data: A Systematic Approach*. Springer-Verlag New York, Inc.

Andrienko, N., Andrienko, G., & Gatalsky, P. (2000). Towards exploratory visualization of spatio-temporal data. In *Third AGILE Conference on Geographical Information Science*.

Andrienko, N., Andrienko, G., Pelekis, N., & Spaccapietra, S. (2008). *Basic Concepts of*

Movement Data Mobility, Data Mining and Privacy, (pp. 15–38). Springer Berlin Heidelberg.

Bartumeus, F., da Luz, M. G. E., Viswanathan, G. M., & Catalan, J. (2005). Animal search strategies: A quantitative random-walk analysis. *Ecology*, *86*(11), 3078–3087.

Bartus, R. T., Dean, R. L., & Fleming, D. L. (1979). Aging in the rhesus monkey: Effects on visual discrimination learning and reversal learning. *Journal of Gerontology*, *34*(2), 209–219.

Basile, B., Hampton, R., Suomi, S., & Murray, E. (2009). An assessment of memory awareness in tufted capuchin monkeys (cebus apella). *Animal Cognition*, *12*, 169–180.

Batschelet, E. (2001). *Circular Statistics in Biology*. Academic Press, London.

Batty, M. (2006). Rank clocks. *Nature*, *444*(7119), 592–596. 10.1038/nature05302.

Benhamou, S., & Riotte-Lambert, L. (2012). Beyond the utilization distribution: Identifying home range areas that are intensively exploited or repeatedly visited. *Ecological Modelling*, *227*(0), 112–116.

Bian (2000). Object-oriented representation for modelling mobile objects in an aquatic environment. *International Journal of Geographical Information Science*, *14*(7), 603.

Boyer, D., & Walsh, P. D. (2010). Modelling the mobility of living organisms in heterogeneous landscapes: does memory improve foraging success? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *368*(1933), 5645–5659.

Burt, W. H. (1943). Territoriality and home range concepts as applied to mammals. *Journal of Mammalogy*, *24*, 346–352.

Byers, J. (2001). Correlated random walk equations of animal dispersal resolved by simulation. *Ecology*, *82*(6).

Calenge, C., Dray, S., & Royer-Carenzi, M. (2009). The concept of animals' trajectories from a data analysis perspective. *Ecological Informatics*, *4*(1), 34–41.

Caselli, C. B., & Setz, E. Z. F. (2011). Feeding ecology and activity pattern of black-fronted titi monkeys (callicebus nigrifrons) in a semideciduous tropical forest of southern brazil. *Primates*, *52*(4), 351–359.

Chapman, C. A., & Peres, C. A. (2001). Primate conservation in the new millennium: The role of scientists. *Evolutionary Anthropology: Issues, News, and Reviews*, *10*(1), 16–33.

Chaves, O. M., Stoner, K. E., & Arroyo-Rodriguez, V. (2011). Seasonal differences in activity patterns of geoffroyia ' s spider monkeys (ateles geoffroyi) living in continuous and fragmented forests in southern mexico. *International Journal of Primatology*, *32*(4), 960–973.

Chen, J., Shaw, S.-L., Yu, H., Lu, F., Chai, Y., & Jia, Q. (2011). Exploratory data analysis of activity diary data: a spacetime gis approach. *Journal of Transport Geography*, *19*(3), 394–404.

Crist, T. O., Guertin, D. S., Wiens, J. A., & Milne, B. T. (1992). Animal movement in heterogeneous landscapes: An experiment with eleodes beetles in shortgrass prairie. *Functional Ecology*, *6*(5), 536–544.

Crist, T. O., & MacMahon, J. A. (1991). Individual foraging components of harvester ants: movement patterns and seed patch fidelity. *Insectes Sociaux*, *38*, 379–396.

Dicke, M., & Burrough, P. A. (1988). Using fractal dimensions for characterizing tortuosity of animal trails. *Physiological Entomology*, *13*(4), 393–398.

Dill, L. M. (1987). Animal decision making and its ecological consequences: the future of aquatic ecology and behaviour. *Canadian Journal of Zoology*, *65*(4), 803–811.

Doerr, E., & Doerr, V. (2005). Dispersal range analysis : quantifying individual variation in dispersal behaviour. *Oecologia*, (pp. 1–10).

Dykes, J. A., & Mountain, D. M. (2003). Seeking structure in records of spatio-temporal behaviour: visualization issues, efforts and applications. *Comput. Stat. Data Anal.*, *43*, 581–603.

E.N. Domingues, D. S., & Vellardi, A. (1987). Correlaes topogeomorfolgicas, geolgicas e de declividades do parque estadual de carlos botelho. *SP. Boletim Tcnico do Instituto Florestal*, *41*, 377–420.

Fernandez, M., Oria, J., Snchez, R., Gonzalez, L. M., & Margalida, A. (2009). Space use of adult spanish imperial eagles aquila adalberti. *Acta Ornithologica*, *44*(1), 17–26.

Fisher, N. I. (1993). Cambridge University Press.

Fragaszy, D. M., Visalberghi, E., & Fedigan, L. M. (2004). *The complete capuchin : the biology of the genus Cebus*. Cambridge; New York: Cambridge University Press.

Frihida, A., Marceau, D. J., & Theriault, M. (2004). Extracting and visualizing individual Space-Time paths: An integration of GIS and KDD in transport demand modeling. *Cartography and Geographic Information Science*, *31*(1).

Fryxell, J. M., Hazell, M., Borger, L., Dalziel, B. D., Haydon, D. T., Morales, J. M., McIntosh, T., & Rosatte, R. C. (2008). Multiple movement modes by large herbivores at multiple spatiotemporal scales. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(49), 19114–19119.

Gallistel, C. R. (1989). Animal cognition: The representation of space, time and number. *Annual Review of Psychology*, *40*(1), 155–189.

Gardner, M. (1970). The fantastic combinations of John Conway's new solitaire game "life". *Scientific American*, *223*, 120–123.

Goodchild, M. F., Yuan, M., & Cova, T. J. (2007). Towards a general theory of geographic representation in gis. *Int. J. Geogr. Inf. Sci.*, *21*(3), 239–260.

Goodman, R. M. (2007). Activity patterns and foraging behavior of the endangered grand cayman blue iguana, cyclura lewisi. *Caribbean Journal of Science*, *43*(1), 73–86.

Graham, P. (1978). Optimal foraging: Movement patterns of bumblebees between inflorescences. *Theoretical Population Biology*, *13*(1), 72–98.

Hagerstrand, T. (1970). What about people in regional science? *Papers in Regional Science*, *24*, 6–21.

Halle, . S. N. C., S. (2000). *Activity patterns in small mammals, an ecological approach.*. Heidelberg: Springer-Verlag.

Handcock, R. N., Swain, D. L., Bishop-Hurley, G. J., Patison, K. P., Wark, T., Valencia, P., Corke, P., & ONeill, C. J. (2009). Monitoring animal behaviour and environmental interactions using wireless sensor networks, gps collars and satellite remote sensing. *Sensors*, *9*(5), 3586–3603.

Hemingway, C. A. (1999). Time budgets and foraging in a malagasy primate: do sex differences reflect reproductive condition and female dominance? *Behavioral Ecology and Sociobiology*, *45*(3), 311–322.

Hill, R. (1999). *Ecological and demographic determinants of time budgets in baboons: Implications for cross-populational models of baboon socioecology.*. Dissertation, University of Liverpool.

Hinely, A. J. (2006). *GIS-Based habitat modeling related to beared capuchin moneky tool use*. Master's thesis, University of Georgia, GA, USA.

Hogan, L. A., Johnston, S. D., Lisle, A. T., Horsup, A. B., Janssen, T., & Phillips, C. J. C. (2011). The effect of environmental variables on the activity patterns of the southern hairy-nosed wombat (lasiorhinus latifrons) in captivity: onset, duration and cessation of activity. *Australian Journal of Zoology*, *59*(1), 35–41.

Horne, J. S., Garton, E. O., Krone, S. M., & Lewis, J. S. (2007). Analyzing animal movements using brownian bridges. *Ecology*, *88*(9), 2354–2363.

Huang, C., Wei, F., Li, M., Li, Y., & Sun, R. (2003). Sleeping cave selection, activity pattern and time budget of white-headed langurs. *International Journal of Primatology*, *24*(4), 813–824.

Hulbert, I. A. R. (2001). GPS and its in animal telemetry: The next five years. *Tracking Animals with GPS*, (pp. 51–60).

Imfeld, S. (2000). *Time, Points and Space: Towards a better analysis of wildlife data in GIS*. Dissertation, University of Zurich.

Jennrich, R. I., & Turner, F. B. (1969). Measurement of non-circular home range. *Journal of Theoretical Biology*, *22*(2), 227–237.

Johnson, C., Parker, K., & Heard, D. (2001). Foraging across a variable landscape: behavioral decisions made by woodland caribou at multiple spatial scales. *Oecologia*, *127*(4), 590–602.

Johnson, J. B., Edwards, J. W., & Ford, W. M. (2011). Nocturnal activity patterns of northern myotis (myotis septentrionalis) during the maternity season in west virginia (usa). *Acta Chiropterologica*, *13*(2), 391–397.

Jonsen, I. D., Myers, R. A., & Flemming, J. M. (2003). Meta-analysis of animal movement using state-space models. *Ecology*, *84*(11), 3055–3063.

Kareiva, P. M., & Shigesada, N. (1983a). Analyzing insect movement as a correlated random walk. *Oecologia*, *56*(2), 234–238.

Kareiva, P. M., & Shigesada, N. (1983b). Analyzing insect movement as a correlated random walk. *Oecologia*, *56*(2), 234–238.

Katerina, V. (2007). Everyday life discoveries: Mining and visualizing activity patterns in social science diary data. vol. 0, (pp. 130–138).

Keating, K. A., & Cherry, S. (2009). Modeling utilization distributions in space and time. *Ecology*, *90*(7), 1971–1980.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., & Engelmann, W. H. (2001). The national human activity pattern survey (nhaps): a resource for assessing exposure to environmental pollutants. *J Expo Anal Environ Epidemiol*, *11*(3), 231–252.

Kraak, M.-j., & MacEachren, A. M. (1994). Visualization of spatial data's temporal component. In *Proceedings, Spatial Data Handling, Advances in GIS Research*, (pp. 5–9).

Kwan, M., & Lee, J. (2005). Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments. *Computers, Environment and Urban Systems*, *29*(2), 93–113.

Kwan, M.-P. (2002). Feminist visualization: Re-envisioning gis as a method in feminist geographic research. *Annals of the Association of American Geographers*, *92*(4), 645–661.

Laube, P., Dennis, T., Forer, P., & Walker, M. (2007). Movement beyond the snapshot dynamic analysis of geospatial lifelines. *Computers, Environment and Urban Systems*, *31*(5), 481–501.

Lenntorp, B. (1976). *Paths in space-time environments : a time geographic study of movement possibilities of individuals*. Dissertation, the Royal university.

Lewis, J. S., & Rachlow, J. L. (2011). Activity patterns of black bears in relation to sex, season, and daily movement rates. *Western North American Naturalist*, *71*(3), 388–395.

Liu, S.-g., Wang, Z.-y., Gong, Z., Chen, F.-f., & Peng, Q.-s. (2006). Physically based modeling and animation of tornado. *Journal of Zhejiang University - Science A*, *7*, 1099–1106.

Lynch Alfaro, J. W., Boubli, J. P., Olson, L. E., Di Fiore, A., Wilson, B., Gutirrez-Espeleta, G. A., Chiou, K. L., Schulte, M., Neitzel, S., Ross, V., Schwochow, D., Nguyen, M. T. T., Farias, I., Janson, C. H., & Alfaro, M. E. (2012). Explosive pleistocene range expansion leads to widespread amazonian sympatry between robust and gracile capuchin monkeys. *Journal of Biogeography*, *39*(2), 272–288.

MacEachren, A. M., & Monmonier, M. (1992). Special content issue: Geographic visualization. *Cartography and Geographic information Systems*, *19*(4), 197–200.

Marsh, L. M., & Jones, R. E. (1988a). The form and consequences of random walk movement models. *Journal of Theoretical Biology*, *133*(1), 113–131.

Marsh, L. M., & Jones, R. E. (1988b). The form and consequences of random walk movement models. *Journal of Theoretical Biology*, *133*(1), 113–131.

McGrady, M. J., Ueta, M., Potapov, E. R., Utekhina, I., Masterov, V., Ladyguine, A., Zykov, V., Cibor, J., Fuller, M., & Seegar, W. S. (2003). Movements by juvenile and immature steller's sea eagles haliaeetus pelagicus tracked by satellite. *Ibis*, *145*(2), 318–328.

McIntyre, N. E., & Wiens, J. A. (1999). Interactions between landscape structure and animal behavior: the roles of heterogeneously distributed resources and food deprivation on movement patterns. *Landscape Ecology*, *14*(5), 437–447.

McMaster, R. B., & Usery, E. L. (2005). *A Research Agenda for Geographic Information Science*. CRC Press, Boca Raton, FL.

Mech, D., & Barber, S. (2002). A critique of wildlife radio-tracking and its use in national parks: a report to the U.S. national park service. *Wildlife Research*.

Mellone, U., Yez, B., Limiana, R., Muoz, A.-R., Pavn, D., Gonzlez, J.-M., Urios, V., & Ferrer, M. (2011). Summer staging areas of non-breeding short-toed snake eagles circaetus gallicus. *Bird Study*, *58*(4), 516–521.

Nathan, R. (2008). An emerging movement ecology paradigm. *Proceedings of the National Academy of Sciences*, *105*(49), 19050–19051.

Nishinari, K., Kirchner, A., Namazi, A., & Schadschneider, A. (2004). Extended floor field ca model for evacuation dynamics. *IEICE Transactions*, *87-D*(3), 726–732.

NOAA, C. P. C. (2012). Pacific sea surface temperature aniamtion.
URL `www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml`

O'Brien, P. H. (1984). Feral goat home range: Influence of social class and environmental variables. *Applied Animal Behaviour Science*, *12*(4), 373–385.

O.C. Negreiros, A. D. G. F. H. C. M. V., A. Custodio Filho, & Netto, B. M. (1995). Anlise estrutural de um trecho de floresta pluvial tropical, parque estadual de carlos botelho, ncleo sete barras (sp brasil). *Revista do Instituto Florestal*, *7*, 1–3.

Patterson, R., & Cox, D. (2005). *Visualization of an F3 tornado within a simulated supercell thunderstorm*. SIGGRAPH '05. New York, NY, USA: ACM.

Peter, G. (2004). Interactive analysis of event data using space-time cube. vol. 0, (pp. 145–152).

Peterson, A. T., Benz, B. W., & Pape, M. (2007). Highly pathogenic h5n1 avian influenza: Entry pathways into north america via bird migration. *PLoS ONE*, *2*(2), e261.

Peuquet, D. J. (1994). It's about time: A conceptual framework for the representation of temporal dynamics in geographic information systems. *Annals of the Association of American Geographers*, *84*(3), 441–461.

Preisler, H. K., Ager, A. A., Johnson, B. K., & Kie, J. G. (2004). Modeling animal movements using stochastic differential equations. *Environmetrics*, *15*(7), 643–657.

Presotto, A., & Izar, P. (2010). Spatial reference of black capuchin monkeys in brazilian atlantic forest: egocentric or allocentric? *Animal Behaviour*, *80*(1), 125–132.

Riley, J. R., Greggers, U., Smith, A. D., Reynolds, D. R., & Menzel, R. (2005). The flight paths of honeybees recruited by the waggle dance. *Nature*, *435*(7039), 205–207.

Rothenwohrer, C., Becker, N. I., & Tschapka, M. (2011). Resource landscape and spatio-temporal activity patterns of a plant-visiting bat in a costa rican lowland rainforest. *Journal of Zoology*, *283*(2), 108–116.

Sands, S. F., & Wright, A. A. (1980). Primate memory: retention of serial list items by a rhesus monkey. *Science*, *209*(4459), 938–940.

Sapolsky, R. M. (2005). The influence of social hierarchy on primate health. *Science*, *308*(5722), 648–652.

Schoener, T. W. (1971). Theory of feeding strategies. *Annual Review of Ecology and Systematics*, *2*(1), 369–404.

Schofield, G., Bishop, C. M., MacLean, G., Brown, P., Baker, M., Katselidis, K. A., Dimopoulos, P., Pantis, J. D., & Hays, G. C. (2007). Novel GPS tracking of sea turtles as a tool for conservation management. *Journal of Experimental Marine Biology and Ecology*, *347*(1-2), 58–68.

Schooley, R. L., & Wiens, J. A. (2003). Finding habitat patches and directional connectivity. *Oikos*, *102*(3), 559–570.

Shneiderman, B. (1996). The eyes have it: a task by data type taxonomy for information visualizations. *Proceedings 1996 IEEE Symposium on Visual Languages*, *0*(UMCP-CSD CS-TR-3665), 336–343.
URL `http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=545307`

Simon, B. (2004). How to reliably estimate the tortuosity of an animal's path:: straightness, sinuosity, or fractal dimension? *Journal of Theoretical Biology*, *229*(2), 209–220.

Stevenson, P. R. (2001). The relationship between fruit production and primate abundance in neotropical communities. *Biological Journal of the Linnean Society*, *72*(1), 161–178.

Stevenson, P. R. (2006). Activity and ranging patterns of colombian woolly monkeys in north-western amazonia. *Primates*, *47*(3), 239–247.

Struhsaker, T. T., & Leland, L. (1979). *Socioecology of Five Sympatric Monkey Species in the Kibale Forest, Uganda*, vol. Volume 9, (pp. 159–228). Academic Press.

Tang, H.-X., Zhou, Q.-H., Huang, Z.-H., Meng, Y.-J., & Huang, C.-M. (2011). Activity patterns and time budgets of the rhesus macaque in karst habitat. *Chinese Journal of Zoology*, *46*(2), 32–38.

Tang, W., & Bennett, D. A. (2010). Agent-based modeling of animal movement: A review. *Geography Compass*, *4*(7), 682–700.

Terborgh, J. (1983). *Five New World Primates. A Study of Comparative Ecology.*. Princeton, NJ: Princeton University Press.

Thoren, S., Quietzsch, F., Schwochow, D., Sehen, L., Meusel, C., Meares, K., & Radespiel, U. (2011). Seasonal changes in feeding ecology and activity patterns of two sympatric mouse lemur species, the gray mouse lemur (microcebus murinus) and the golden-brown mouse lemur (m. ravelobensis), in northwestern madagascar. *International Journal of Primatology*, *32*(3), 566–586.

Tian, H., Ma, X., Wang, H., Song, G., & Xie, K. (2010). A novel approach to estimate human space-time path based on mobile phone call records. In *Geoinformatics*, (pp. 1–6).

Tracey, J. P., Woods, R., Roshier, D., West, P., & Saunders, G. R. (2004). The role of wild birds in the transmission of avian influenza for australia: an ecological perspective. *Emu*, *104*(2), 109–124.

Trullier, O., Wiener, S., Berthoz, A., & Meyer, J. (1997). Biologically-based artificial navigation systems: Review and prospects. *Progress in Neurobiology*, *51*, 483–544.

Tufte, E. (1983). *The Visual Display of Quantitative Information*. Graphics Press.

Tukey, J. W. (1997). *Exploratory Data Analysis*. Addison-Wesley Publishing Company.

Turchin, P. (1998). *Quantitative Analysis of Movement: Measuring and Modeling Population Redistribution in Animals and Plants*. Sinauer Associates, Sunderland, Mass.

Turner, R. G., M.G., & ONeill., R. (2001). *Landscape Ecology in Theory and Practice: Pattern and Process*. The Johns Hopkins University Press.

Urios, V., Soutullo, A., pez, L., pez, P., Cadah, a, L., Limi, ana, R., & Ferrer, M. (2007). The first case of successful breeding of a golden eagle aquila chrysaetos tracked from birth by satellite telemetry. *Acta Ornithologica*, *42*(2), 205–209.

Van Winkle, W. (1975). Measurement of non-circular home range. *Journal of Wildlife Management*, *23*, 118–123.

Vieira, E. M., Baumgarten, L. C., Paise, G., & Becker, R. G. (2010). Seasonal patterns and influence of temperature on the daily activity of the diurnal neotropical rodent necromys lasiurus. *Canadian Journal of Zoology-Revue Canadienne De Zoologie*, *88*(3), 259–265.

Vrotsou, K., Ellegard, K., & Cooper, M. (2007). Everyday life discoveries: Mining and visualizing activity patterns in social science diary data. (pp. 130–138).

Webb, S. L., Riffell, S. K., Gee, K. L., & Demarais, S. (2009). Using fractal analyses to characterize movement paths of white-tailed deer and response to spatial scale. *Journal of Mammalogy*, *90*(5), 1210–1217.

Weiss, E., Corona, L., & Schultz, B. (2012). Sex differences in musculoskeletal stress markers: Problems with activity pattern reconstructions. *International Journal of Osteoarchaeology*, *22*(1), 70–80.

Zhou, Q., Wei, F., Huang, C., Li, M., Ren, B., & Luo, B. (2007). Seasonal variation in the activity patterns and time budgets of trachypithecus francoisi in the nonggang nature reserve, china. *International Journal of Primatology*, *28*(3), 657–671.

Zollner, P. A., & Lima, S. L. (1983). Analyzing insect movement as a correlated random walk. *Oecologia*, *56*(2), 234–238.