# A FUZZY LOGIC APPROACH TO SPATIAL MANAGEMENT OF SMALL-SCALE FISHERIES


by

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## Abstract

Fishers are an integral part of the marine ecosystem; where and how fishers allocate their fishing effort can directly affect biological outcomes. Nonetheless, the human dimensions of fisheries are often not well understood, even though the ability to anticipate fishers' response to spatial regulations is a key aspect of successful management. My thesis addresses this challenge by developing a marine spatial management tool that balances both human and conservation variables. I conduct an empirical investigation of small-scale fishers' spatial use patterns with the aim of understanding how fishers' preferences and perceptions of the marine environment affect their selection of fishing locations. I find that fishers tend to fish within preferred resource spaces that are bounded by the extent of their mental maps, and that are always considered to be safe. I integrate fishers' preferences in a fuzzy logic expert system that I develop for zoning marine spaces in data poor conditions. This system, the protected area suitability index (PASI), assesses the suitability of a site for being protected from fishing by balancing fishers' preference for the site with the site's conservation value. Sites that are considered to be highly suitable for protection are those that have low fisher preference and high conservation value. The PASI estimates site suitability scores that range from 0 to 10, where 10 indicates that a site is very suitable for protection. I applied the PASI in a case study of a proposed marine protected area in Sabah, Malaysia. At least 58% and up to 75% of the time, the PASI's assessment of site suitability matched a zoning plan for no take areas that was designed through a collaborative community process. This demonstrates that the PASI is appropriate for conducting rapid site prioritisation in data poor regions of the world, and can be used as an alternative to data, time, and financially demanding spatial planning methods.

## Preface

Ethics approval for this research was granted by the University of British Columbia's Behavioural Research Ethics Board, certificate number H07-01007.

A version of Chapter 3 has been published. Teh LCL, Teh LSL (2011) A fuzzy logic approach to marine spatial management. Environmental Management 47:536-545. I conceptualized the study framework, conducted the field research, and wrote the manuscript. LSL Teh assisted with field work and edited the manuscript.

A version of Chapter 2, titled "Preferred resource spaces and fisher flexibility: implications for spatial management of small-scale fisheries", co-authored with LSL Teh and MJ Meitner, has been resubmitted with revisions to a peer reviewed journal. I conducted the field research, data analysis, and wrote the manuscript. LSL Teh assisted with field work, prepared the map figures, and edited the manuscript. MJ Meitner contributed to manuscript writing.

A version of Chapter 4, titled "A tool for site prioritisation in marine protected areas under data poor conditions", co-authored with LSL Teh and TJ Pitcher, has been submitted to a peer reviewed journal. I conducted the data collection, data analysis, and wrote the manuscript. LSL Teh assisted with data collection and edited the manuscript. TJ Pitcher contributed to manuscript writing.

VBA code for the fuzzy logic model is adapted from a version written by WWL Cheung of the Fisheries Centre, University of British Columbia.

Robecca Jumin contributed information about the community consultation process described in Chapter 5 and provided maps that were used for analysis in the chapter.

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To my family

# Chapter 1: Introduction

The global decline in fisheries witnessed in the last 50 years signals the need for a new direction in managing the marine environment. This need may be fulfilled by adopting an approach that accounts for human dimensions in fisheries and conservation management (Jentoft 2000, Johannes et al. 2000, Mascia 2003). The multi-species nature of coral reef fisheries, and the existence of fishing communities that interact closely with the inshore reef environment, make managing this ecosystem a complex task (ISRS 2004). Many coral reef fisheries are politically and socio-economically marginalized, so they are simply not managed (Teh et al. 2007, Sale 2008). In fact, in many regions of the world, basic parameters such as the number of fishers, especially small-scale fishers, remains unknown (Zeller and Pauly 2007). To this extent, I estimated that there are approximately 20 million small-scale fishers globally (Teh and Sumaila in press), most of whom are concentrated in developing countries in Asia. The challenge of managing the small-scale fishing sector, particularly where central decision makers lack the interest and resources for monitoring, research, and enforcement (Pauly 1997), is an issue that warrants our attention.

Where capacity for managing coral reefs exists, marine protected areas (MPA) are a common tool (Sale 2008). MPAs have demonstrated some success in sustaining fisheries and coastal communities (Russ 2002, Halpern 2003, Russ et al. 2004), but many are merely legislated 'paper parks'. In order for marine protected areas to work, they must be able to protect habitat effectively, which entails changing human behaviour (Sale 2008). Failure to do so results in MPA conservation objectives being undermined by poor user compliance (Kelleher et al. 1995, Sethi and Hilborn 2008). Therefore, improving compliance with MPA regulations is a route towards management success, and it can be achieved by addressing and integrating resource users' (fishers') perspectives meaningfully into MPA design, planning, and implementation stages (Sharma 2008).

To date, site selection tools that have been applied to MPA zoning generally require complex models and/or extensive data sets to produce meaningful results (e.g. Marxan, Ecospace). Such models are dependent on data quality and quantity, the lack of which can stall action in favour of collecting more data (Ban 2008, Grantham et al. 2009). Therefore, they are not practical for many tropical developing country fisheries where time, funds, and expertise for data collection and application are often lacking (Johannes 1998).

## 1.1 Research objective

My research objective is to contribute to the improvement of area based management by developing a spatial management tool that balances human preferences with conservation criteria. I propose a fuzzy logic expert system that evaluates the suitability of marine sites for inclusion in protected areas. A site's suitability will be determined by fishers' preference for it, as well as its conservation value. The specific issues I address in my research are:

1. What factors influence small-scale fishers' spatial use patterns?
2. How can human perceptions be integrated in marine spatial planning?
3. Is a fuzzy logic based spatial planning approach viable for zoning marine protected areas?

## 1.2 Marine protected areas

Marine protected areas are a common intervention strategy that is used to achieve biodiversity conservation and sustainable fisheries management in many developing countries. In 1985 there were 430 MPAs worldwide (Agardy et al. 2003), compared to around 4435 MPAs by the end of 2006 (Wood 2007). Much of this increase can be attributed to countries' obligation to the Convention on Biological Diversity mandate, which stipulates that 10% of all habitats have to be represented within protected areas by 2010. The functionality of marine protected areas is based on the theory that restricting extractive activities will improve the survivorship of fishes and other marine organisms that reside within the protected area (Sale 2008). Studies verifying this theory have shown MPAs to be effective in conserving habitats and populations (Gell and Roberts 2003, Halpern 2003), thereby providing benefits for fisheries through the spillover effect (Russ et al. 2004), as well as for biodiversity conservation.

On the other hand, some authors have found that existing evidence showing ecological benefits from MPAs are insufficient, owing to the *ad hoc* design of many MPAs, and statistical challenges in establishing cause and effect relationships (Alder 1996, McClanahan 1999). Furthermore, the ability of MPAs to generate socio-economic benefits has also been questioned (Carr 2000), and in some cases fishers have ended up bearing the costs of MPAs (Sharma 2008). There is also the danger of overusing and simplifying MPAs as a blanket solution for all marine conservation problems, a move that may potentially threaten the progress of the science itself (Agardy et al. 2003, Sale 2008).

The basic questions of determining MPA location and size depends on the specific objective for which the MPA was created, and there is no resounding consensus on what combination of size, shape, and spacing is best (Botsford et al. 2003). Criteria for siting MPAs have largely been focused on ecological principles, such as maximising habitat heterogeneity, including vulnerable habitat, and including rare and endemic species (Botsford et al. 2003, Roberts et al. 2003). One general rule of thumb is to avoid areas that are frequently used by humans or that are subject to natural disturbances (Botsford et al. 2003). The key to an MPA's success lies in its ability to actually protect its designated protected zones (Sale 2008), which points to user compliance as being a main ingredient for success. Resistance from fishers to cooperate and accept MPA regulations can effectively cancel out benefits arising from a MPA (Botsford et al. 2003); therefore managers should focus on creating conditions that facilitate compliance behaviour from fishers.

## 1.3 How fishers choose fishing grounds: an overview of fishers' behaviour

The way fishers determine where, when, what, and how to fish, as well as their reaction to regulations, can greatly impact the success of attaining fisheries and conservation objectives (Gambino et al. 2003). The importance of understanding fishers' behaviour in order to successfully manage fisheries is widely recognised (Hilborn 1985, Salas and Gaertner 2004). For example, a marine reserve network in California that was designed by fishers turned out to be more efficient in satisfying biodiversity and fisheries requirements compared to networks designed by non-fishing stakeholders. Further, numerical optimization routines with fishing effort information performed better in representing habitat and reducing fisheries impacts than routines without fishing effort information (Klein et al. 2008a). These results highlight how incorporating fishing effort allocation information can improve the design of marine protected areas, and also make the case for seeking to understand why fishers go where they do.

Fishing effort allocation is usually studied using concepts from ecology and economics. The optimal foraging theory and the ideal free distribution theory are widely assumed to reflect fishers' decision-making on a day to day basis (Abrahams and Healey 1990, Begossi 1992, Swain and Wade 2003, Aswani and Lauer 2006, Abernethy et al. 2007). Optimal foraging theory states that animals, or people, focus on consuming the most energy while exerting the least amount of energy. It examines two decisions: what prey or patch to consume, and when to abandon a patch. Ideal free distribution theory explains the distribution of animals with respect to their resources. It states that predators should forage to equalize their rates of return, so regardless of where they are, animals will distribute themselves so that they receive equal amounts of the resource.

Aswani and Lauer (2006) applied optimal foraging theory to study the fishing strategies of artisanal fishers in the Solomon Islands, and found that there was a positive correlation between overall time allocation and seasonal habitat productivity. Abrahams and Healey (1990) found that ideal free distribution theory could explain the relationship between vessel distribution, catch rate, and fish distribution in the British Columbia salmon troll fishery. On the other hand, the ideal free distribution theory was not able to account for the behaviour of artisanal coral reef fishers in Anguilla, where fishers' movement and ability to fish were found to be limited by physical and socio-economic factors (Abernethy et al. 2007).

Economic theory predicts that fishers will redistribute fishing effort across fishing locations or fisheries when there is a differential in expected economic return, so that fishing effort is equally distributed to equalize the profit among fishers (Hilborn and Kennedy 1992, Robinson and Pascoe 1997). Empirical studies suggest that economic theory does account for observed fishing behaviour (Hilborn and Kennedy 1992, Guest 2003), up to a certain extent. However, there are also some aspects of fishing behaviour that cannot be explained, or are inconsistent with those predicted by theory (Béné and Tewfik 2001, Guest 2003, Salas and Gaertner 2004, Abernethy et al. 2007). Profit maximization models work well in single species fisheries, but less so in complex multi-species fisheries where ecosystem interactions and fishing costs have to be considered for multiple species. In addition, when individual fishers rather than fleets are being considered, the population in question is no longer homogenous, and variables such as risk attitudes and fishing experience and knowledge, which influence the selection of sites and effort allocation, have to be accounted for (Salas et al. 2004, Abernethy et al. 2007).

In fact, fishers' behaviour is driven by a combination of external and internal factors such as weather, technology, skills, social constraints, and risk attitudes (Béné and Tewfik 2001, Wilen et al. 2002, Gambino et al. 2003, Salas and Gaertner 2004). A study of small scale fisheries in

Indonesia revealed that monthly fishing gear allocation was not dependent on catch but mostly on seasonal fluctuations in rainfall (Wiyono et al. 2006). Likewise, seasonal dynamics of the lobster fishery in Turks and Caicos were found to be governed by resource availability rather than financial profit motivation alone (Béné and Tewfik 2001). Social dynamics can also have a key role in influencing fishing behaviour. For example, fishers' participation in the queen conch and spiny lobster fisheries in the Turks and Caicos Islands was driven by social status, whereby fishers wanted to be perceived as having superior skills over others (Béné and Tewfik 2001).

Understanding the risks that fishers face can also provide insight to their behaviour. Fishers have to deal with environmental, economic, and political uncertainties in their daily activities. Small-scale fishers in developing countries, in particular, often live in poverty, which, when coupled with factors such as lack of institutional support for securing welfare, makes them particularly vulnerable to economic or environmental downturns (Béné 2003, Allison 2005). Faced with long term insecurity and uncertainty, fishers are forced to behave in ways that secure immediate survival. In effect, this induces fishers to avoid making riskier long term commitments that may actually lead to improved livelihoods (Wood 2003, Barratt 2009). Thus, in poverty situations, fishers may exhibit risk averse behaviour and choose "a coping level of poverty" (Wood 2003), a strategy which ultimately dictates fishing decisions.

Although the fishing behaviour literature provides extensive material on explaining the motivations for fishing, an issue that has not been addressed is the role of fishers' environmental perception in influencing behaviour, and how knowledge of fishers' perceptions can be integrated and used to improve management strategies such as zoning. Essentially, fishers make decisions about fishing based on their interpretation of the environment (McKenna et al. 2008). Therefore, differences between predicted and observed behaviour may be due to fishers responding to socio-economic and/or environmental cues that are apparent to them, but not obvious to managers who have different perspectives.

## 1.4 Fishers' perceptions

Humans make judgements based on the world as they see it, not as it is (García-Mira and Real 2005). The world as seen through a fisher's perspective is represented by their mental map, which is generated from the fishers' perception of biological and social features in the marine environment, and how these features interrelate to each other (Feinberg et al. 2003). Such perceptual constructs may or may not be accurate portrayals of reality, but are the basis upon which fishers make their daily movement and fishing decisions (McKenna et al. 2008). Studies of fishers' perceptions focus on capturing their local ecological knowledge. Detailed documentations of fishers' understanding of the marine environment reveal how their decisions about gear, timing, and fishing location are attuned to factors such as currents, winds, moon phases, and fish behaviour (Forman 1967, Cunningham et al. 2004).

Fishers' perceptions and mental maps are inherently subjective and contain only attributes that are perceived to be valuable by the mapper, that is, the fisher. Thus, fishing grounds have attributes attached to them that are relevant and important to fishers for their daily decision-making (Sperb and Cabral 2004, de Kok et al. 2000), but these spatial attributes are seldom recognised or considered relevant by managers who operate on a different level. The quality of MPA management can be improved (and hence promote higher compliance) by developing a system that is able to combine and synthesize perception and spatial behaviour information with ecological and socio-economic data.

## 1.5 Fuzzy logic

Fuzzy logic, first developed by Zadeh (1965), is an approach for handling complex problems using reasoning that is approximate as opposed to precise, formally deduced logic. The key difference between fuzzy logic and probability theory is that the former is interested in capturing partial truths, that is, how to reason about things that are not wholly true or false, while the latter is concerned with making predictions about events based on a partial state of knowledge.

Fuzzy logic is derived from fuzzy set theory whereby subjects in a set have degrees of membership, described by membership functions, and where each subject can belong to one or more fuzzy sets. Membership in a fuzzy set is denoted by a membership value between 0 and 1; it can be thought of as the possibility of association of a particular subject with a particular set, as opposed to the probabilistic likelihood of an event occurring. Fuzzy logic is useful in situations where vagueness exists, there are no clear cut definitions, and results cannot be categorised as "true" or "false" outcomes. It is appropriate where uncertainty exists in our understanding of the subject, such as in the case of assessing the suitability of MPA sites, which are influenced by ecological and socio-economic variables, as well as human perceptions and values.

## 1.6 Thesis overview

My thesis consists of this introductory chapter, 4 main chapters, and one concluding chapter. Each of the 4 main chapters (Chapters 2-5) addresses a part of my research objective, and the final chapter summarises my findings and contribution to the field of knowledge on fisher behaviour and marine spatial management. Below, I describe the structure of my thesis.

### 1.6.1 Chapter 2: Preferred resource spaces and fisher flexibility: implications for spatial management of small-scale fisheries

This chapter is an empirical investigation of small-scale fishers' spatial use patterns. I extract spatially explicit fisheries data from catch logs kept by fishers in Pulau Banggi, Sabah, and from semi-structured interviews with fishers in Pulau Banggi and Semporna, Sabah. I use Analysis of Similarity (ANOSIM) in PRIMER 5 software to test for differences in fishing trips by 3 variables: net revenue from the sale of fish per trip (MYR $trip^{-1}$); fish catch (kg $trip^{-1}$); and one way distance travelled from residence (km). I find that contrary to profit maximization theory (Hilborn and Kennedy 1992, Robinson and Pascoe 1997), fishers are not motivated by net revenue alone. Rather, most fishers tend to fish where the net revenue to distance ratio is maximized. Further, I find that the majority of fishers are inflexible to changing their spatial behaviour, and use the concept of mental maps to explain fishers' spatial preferences.

### 1.6.2 Chapter 3: Integrating human dimensions to marine spatial management using a fuzzy logic approach

This chapter presents the rationale for adopting a fuzzy logic approach to marine spatial management, and outlines the framework of the protected area suitability index (PASI). I describe how the PASI was developed, and demonstrate how the PASI operates by applying the tool to estimate the suitability of a marine site in Pulau Banggi for protection from fishing. I show that the PASI can integrate fishers' perspectives of their fishing environment with scientific data to produce results that aim to be acceptable to resource users and fulfill biodiversity objectives at the same time.

### 1.6.3 Chapter 4. A tool for site prioritisation in marine protected areas under data poor conditions

In this chapter I apply a working model of the PASI to estimate the suitability of 18 fished sites in Pulau Banggi and 11 dive sites closed to fishing in the Sugud Island Marine Conservation Area (SIMCA), Sabah, for protection from fishing. The PASI requires data input for 8 attributes for every site that is evaluated – fish catch (kg $trip^{-1}$); depth (m); distance from closest village (km); net revenue (MYR $trip^{-1}$); endangered species occurrence (scale of 1-10); hard coral cover (%); and fish abundance (# of fish per $100m^2$). From these attributes, inferences of fishers' preferences and conservation value per site are made and weighted to produce a final site suitability score. I use one way analysis of variance (ANOVA) to compare whether there is a significant difference between average estimated site suitability scores in Banggi and in SIMCA. I find that the PASI is able to distinguish between sites that are preferred fishing locations and those where few fishers fish. I then conduct sensitivity analysis to test how robust the PASI is. The PASI is relatively insensitive to eliminations in data, thus is well suited for use in data poor and data rich fisheries alike.

### 1.6.4 Chapter 5. Comparing marine protected area site selection using a community based and fuzzy logic approach

This chapter examines the degree to which PASI site suitability estimates overlap with no take areas selected for protection by communities in Banggi, Sabah. The zoning plan of the Maliangin Sanctuary, situated in southern Banggi, forms the basis of the comparative analysis. I use the PASI to estimate protection suitability scores for 11 sites in the vicinity of Maliangin Sanctuary. I assess overlap by calculating the number of convergently classified sites divided by the total number of sites, and compute Cohen's Kappa statistic for inter-rater agreement. I then use multidimensional scaling (MDS) to examine the extent to which attributes used in the PASI to measure fishers' site preference actually did so. I find that there is 75% overlap in sites chosen for protection when site suitability scores are estimated using only the suite of fisher preference attributes and the attribute 'endangered species'. When coral reef health indicators are added, overlap decreases to 58%. However, both overlaps are not statistically significant. MDS shows clustering in sites that are highly preferred by fishers, as well as clustering in sites with low suitability when factored by the PASI's preference subcomponent score. Overall, suitability scores estimated by the PASI appear to reflect fishers' spatial preference. The distinction is greatest when fisher preference subcomponent scores are analysed alone, while total suitability scores have to be interpreted with the polar criteria of human use and conservation in mind.

### 1.6.5 Chapter 6. Conclusion

I synthesize my main findings and discuss their relevance to advancing spatial management of small-scale fisheries. I also discuss assumptions and address limitations of the research, and suggest how the PASI can be practically applied in the field. Lastly, I propose topics for future study that can build upon the results and insights that I have presented.

# Chapter 2: Preferred resource spaces and fisher flexibility: implications for spatial management of small-scale fisheries

## 2.1 Introduction

Effective fisheries management is an urgent matter in many developing countries, where most of the world's small-scale fishers are concentrated (Andrew et al. 2007). Many fisheries management interventions are in the form of spatial regulations that limit or otherwise change fishers' access to fishing grounds. Yet, they rarely consider whether fishers are able or willing to make the change, despite the fact that the way fishers distribute their fishing effort can directly influence the ecological and social-economic outcomes of management objectives (Smith and Wilen 2003).

This chapter will investigate the spatial preferences of small-scale fishers in Sabah, Malaysia, within the framework of mental maps and perceptions. I will examine how adherence to spatial preferences can influence fishers' willingness and ability to adapt to imposed spatial regulations. In particular, I suggest that fishers fish within a preferred resource space (PRS), the usage of which is stable and relatively insensitive to external impacts. Insights drawn from this chapter can be used to further understand what and how unseen processes influence fishers' spatial preferences, and can be applied to enhance the effectiveness of marine spatial management.

The 'spatialization' of fisheries management (Kaplan et al. 2010) is reflected in the trend towards spatially oriented tools like territorial rights-based fishing access and particularly, marine protected areas (MPAs) (St. Martin 2004, Kaplan et al. 2010). Being able to anticipate fishers' behaviour is central to successful spatial management (Smith and Wilen 2003, Fulton et al. 2011, Kaplan et al. 2010); however, efforts to understand how fishers respond to spatial regulations are limited compared to the amount of research dedicated to the biological aspects of marine spatial management (Charles and Wilson 2009, Kaplan et al. 2010). Consequently, fisher behaviour tends to be simplified. Superficial treatment of human behaviour as an integral component of the marine ecosystem, especially where fishing communities are situated within MPAs, can lead to unexpected outcomes such as noncompliance (Hatcher et al. 2000, Hønneland

2000, Fulton et al. 2011) or negative ecological results (Dinmore et al. 2003, Suuronen et al. 2010).

Understanding fishers' fishing behaviour is thus an important and necessary component of fisheries management (Branch et al. 2006, Hilborn 2007, Fulton et al. 2011). In particular, the role that perceptions play in influencing fishers' decisions is crucial, but rarely considered (St. Martin 2001, Charles and Wilson 2009). Most studies measure behaviour against variables that are deemed relevant and important from the point of view of scientists and managers, or for which data are collectable (Robbins 2003). Thus, fisheries economists tend to treat fishers as profit maximisers who will redistribute fishing effort across space until profit is equalized among fishers (Hilborn and Kennedy 1992, Robinson and Pascoe 1997), even though there is much empirical evidence to call into question the theory of rational choice (Kahneman and Tversky 1979, 2000, Tversky and Kahneman 1981, Gigerenzer and Selten 2002). Alternatively, ecologically oriented fisheries scientists find that fishers' effort allocation mimics the foraging behaviour of predators in a natural environment (Bertrand et al. 2007). Nonetheless, fisher behaviour models are only able to partially predict fishers' spatial choices and fishing effort distribution (Béné and Tewfik 2001, Guest 2003, Salas and Gaertner 2004, Abernethy et al. 2007).

The explanatory value of models is compromised because they base their predictions on variables that may not actually be significant from fishers' perspectives in their decision-making process (St. Martin 2001, Robbins 2003). This can occur due to heterogeneity among fishers, or true state dependence, whereby a previous condition shapes expectations, constraints, or attitudes (Wilen et al. 2002, Smith 2005). For example, fishers' past fishing experiences can influence future uses of particular fishing locations, as can fishers' individual preferences for spatial attributes such as a deep or non-crowded fishing site. Conceptually, it implies that observed spatial choices are the result of individual fishers acting upon perceptions.

One method of spatially capturing fishers' perceptions of their marine environment is through the use of mental maps. Mental maps represent an individual's knowledge of an area as seen through each person's perceptions and memories. A fisher's mental map is generated from their perception of biological and social features in the marine environment, and how these features interrelate to each other (Feinberg et al. 2003). Such perceptual constructs may or may not be accurate portrayals of reality, but are the basis upon which fishers make their daily movement and fishing decisions (Feinberg et al. 2003, McKenna et al. 2008). As such, the marine space is not homogenous, but rather each unit of space has certain attributes conferred upon it by fishers (de Kok et al. 2000, Sperb and Cabral 2004). Uncovering these attributes and determining which ones are important to fishers can help managers to better anticipate fishers' spatial decisions.

### 2.1.1 Study site

I conduct this study in the state of Sabah, located on the Malaysian part of Borneo. The two main study sites are Pulau Banggi (from here on referred to as Banggi) off the northern tip of Sabah, and the Semporna group of islands in southeast Sabah (Figure 2.1). Banggi is the largest island in Malaysia with a total area of 700 $km^2$ (Anon 2003). It is comprised of two main islands as well as about 50 smaller outlying islands. Banggi straddles the Sulu Sea to the east and South China Sea to the west, and is located approximately 30km across the Banggi Channel from the nearest mainland town of Kudat. It is sparsely populated and had an estimated population of 16,000 in 2005 (Anon 2005), with communities situated inland and along the coast. Fishing is the main economic activity in coastal communities (Teh et al. 2005), although in the past 5 years an injection of government funded infrastructure and plantation projects has generated limited employment on land. Study sites in Banggi were situated on the main islands of Banggi and Balambangan, as well as Malawali and Maliangin islands.

The Semporna group of islands lies east of the district of Semporna, which had a population of 140,400 in 2010 (Department of Statistics, 2010). Study sites in Semporna were situated on the islands of Mabul, Dinawan, Omadal, and Bum Bum, which ranged in size from about 25 households to 350 households. Two of the islands, Mabul and Dinawan, are relatively far from the mainland, with Dinawan being about 40km southeast of Semporna town, while Bum Bum and Omadal are about 12km and 20km from Semporna town, respectively. The economy of Semporna islands is mixed, with fisheries and seaweed farming being important activities for island inhabitants (SIDP 2001), while on Mabul there is a developed tourism sector.

The use of marine space for fishing in Sabah is regulated under a provision in the Malaysian Fisheries Act, which defines four zones for specific fishing gear and vessel types. Waters less than 5 nautical miles from shore are reserved solely for small-scale fishers using traditional fishing gear and owner-operated vessels. However, these zoning regulations are not enforced due to limited manpower and resources. As a result, inshore waters are essentially treated like a *de facto* open access system (Teh et al. 2007). From time to time, small-scale fishers from mainland Sabah and Semporna are seen fishing in Banggi waters, while commercial purse seine and trawl vessels are regularly sighted by traditional fishers during the night. Similar open access conditions prevail in Semporna. At the time of this study, the proposed Tun Mustapha Park, a one million hectare multi-use managed area surrounding Banggi, was in the process of being established. In Semporna, a multi-zoned marine park was created in 2004 about 15km north of Semporna town, but had little effect on the activities of fishers in the study sites. The presence of popular dive resorts near two study sites acted as *de facto* marine parks, as fishers were often chased away by resort staff from fishing near the resorts.

I focus on Sabah's small-scale reef fisheries, which are artisanal in nature and acknowledged to be in decline (Pilcher and Cabanban 2001, Teh et al. 2007, Ng and Justin 2009). Small-scale fishers in Sabah use multiple gears including hook and line, gillnet, traps, spear gun, and long line. Some fishers specialize in only one type of gear, such as bottom gillnets, while others make use of multiple gears. Fishers fish a variety of species including demersal reef fishes, reef associated pelagics, and invertebrates.

Fishers in Banggi and Semporna typically make day trips out to fishing grounds, departing from their villages at dawn. Hook and line fishers return at noon then go out to sea again in the afternoon until dusk, or may stay out the entire day until evening. Gillnet fishers usually fish during the evening and early morning before dawn. Fishers use wooden plank boats, the majority of which range between 1.8m and 5.5m in length, and are powered by 7 to 13 horsepower inboard water pump engines, with maximum of up to 40 horsepower. A small number of fishers have fibreglass boats with larger outboard engines, provided by government aid funds. Small-scale fishers in Banggi and Semporna did not use GPS (global positioning system), fish finders, or other devices to aid navigation or for locating fish at the time this study was conducted. Some fishers carried cellular phones while at sea, but did so primarily for safety reasons. Fishers usually fished alone. Groups of two or three fishers would sometimes go fishing together, with each using their own boat. Multi-day fishing trips were also taken, but were less common.

## 2.2 Methods

### 2.2.1 Catch logs

I initiated a catch log programme in Banggi in May 2007 to monitor fishers' spatial use patterns and collect fisheries data (Teh and Teh 2007). The catch log programme was not extended to Semporna due to limited time availability and the lack of field assistants to collect and distribute catch logs. Participating fishers filled in one catch log form for every fishing trip that was taken over a one month period, for four cycles spanning May 2007 to September 2008. In total, 1207 catch logs were filled, of which 1017 had complete location, revenue, and fuel cost data (Table 2.1). Fishers' participation fluctuated for reasons including finding temporary employment, taking time off to build a boat, or loss of interest. Each cycle corresponded with different fishing seasons to capture the peak and lowest periods of fishing.

I went from house to house at 6 villages to recruit fishers to participate in the catch log programme. A seventh village, Damaran, was subsequently recruited after I left the field site, and joined the catch log programme in the second cycle. Due to poor transportation infrastructure, only villages that were easily accessible by boat or road were selected for inclusion in the catch log programme. The estimated number of fishers in Damaran was 50; Kaligau-15; Kobong-8; Lok Tohog-35; Maliangin-12; Perpaduan-39; and Singgahmata-20. No incentives were provided to participate, and roughly 25% of the fishers I approached chose not to participate. Fishers who volunteered to participate were provided with catch log forms and a stationery kit. Two to three follow up visits were conducted in the initial cycle, during which forms were checked for clarity and consistency, and fishers were able to give their feedback regarding the catch log.

Catch logs recorded fishers' fishing location, gear, total trip time, revenue from the sale of fish, total fish catch (weight by species), fuel cost, and weight of fish sold for every day that fishers made a fishing trip. Catch log data were entered into an Access database which I built and maintain. Distance to fishing locations was measured using the ruler function on Google Earth; I measured the route to travel one way by boat between fishers' beach front landing and fishing grounds. Activities that involved travelling additional distance, such as repositioning boats, setting gillnets, and trolling, were not measured.

A list of fishing location names was provided on the catch log. The list was compiled by me and Louise Teh, another graduate student from the University of British Columbia Fisheries Centre, based on observations of, and participation in fishing trips, interviews, and informal conversations with fishers in the Banggi area since 2004. As such, the list was fairly comprehensive. Fishers ticked off the fishing location that they travelled to each day, and were free to add other locations that were not on the list. Catch logs were not accompanied by maps for fishers to mark where they had gone to fish. This decision was made because I felt it would be faster and easier for fishers to simply tick off a box rather than having to familiarize themselves with maps, a skill that not all fishers were accustomed to. I verified fishing locations with each participant to make sure that both parties were clear on which names referred to which fishing location, as names and knowledge of some fishing locations varied by village. Whenever possible, I also used a GPS to mark fishing locations, both existing ones on the list as well as new ones recorded by fishers. Otherwise, new fishing locations were approximated based on positions indicated by fishers on a base map of Banggi (Appendix A).

All fishing locations were grouped into one of seven fishing zones (Table 2.2). Spatial data were presented by zones rather than individual fishing location for several reasons. First, some fishing locations were located close together and had similar attributes, so it was more efficient to treat them as a group rather than individually. Second, some fishers identified specific fishing locations by name while others identified only the general area in which the fishing location was found. To avoid potentially over or under representing certain fishing locations, I decided to use the broader classification of fishing zones as the unit of analysis. Third, fishing zones were used to highlight spatial use patterns and to effectively bring out differences that may otherwise have been lost when viewed at the level of fishing locations. Fishing zone boundaries were defined geographically, as I clustered fishing locations that were close to each other to form a zone.

### 2.2.2 Interviews

Interviews were carried out by me and a research assistant in April and May 2009 with a total of 75 fishers - 50 from 7 villages in Banggi and 25 from 4 villages in Semporna. I selected villages to provide a geographical representation of fishing activities in the study sites. Interviews were carried out in Malay, and typically lasted between 45 minutes and an hour. I undertook convenience sampling, whereby I went door to door to ask for a fisher who was willing to be interviewed. I first informed all potential interviewees of the study objective and the intended use of the information, and ensured that all interviews would be conducted anonymously. I also emphasized that fishers were free to refuse to participate. Once a fisher made a decision and agreed to be interviewed, I proceeded with semi-structured questions pertaining to their fishing activities, spatial use preferences and patterns, and perceptions of the marine environment.

All interviews included a mapping exercise, which was first conducted with 12 catch log participants in Banggi in 2007. At that time, fishers were initially asked to draw their fishing grounds with the intent of creating mental maps. However, fishers were reluctant to draw, saying that they “did not know how”. To avoid creating a situation where fishers felt pressured and uncomfortable with a task, I stopped asking fishers to draw. Instead, I asked fishers to point out their fishing grounds on prepared paper maps. I first oriented fishers by marking their village of residence, and indicated prominent land marks such as nearby islands and bays, as necessary. I asked open-ended questions about the fishers’ travel route, the movement and location of fishes, and characteristics of their fishing grounds. In 2009, mapping exercises followed the same procedure and used identical paper maps as in 2007. Subsequent informal conversation with fishers in Banggi contributed further insight about their knowledge of fish behaviour, fishing history, and fishing patterns.

None of the interviewees were reluctant to discuss their fishing locations, although they were aware that the information would be used in reports written and seen by ‘other people’. Fishers freely revealed details such as specific spots to find commercially expensive fish, places suitable for certain gears, and seasonal locations. Such knowledge might be considered sensitive information in other fisheries, and should be treated with respect and discrepancy (Maurstad 2002). I have thus chosen not to identify fishing locations or to disclose extensive location specific details in this chapter.

### 2.2.3 Data analysis

I analysed catch log data for differences in fishing zones by applying an analysis of similarities (ANOSIM) using PRIMER 5 software to test for differences in fishing trips grouped by fishing zone. My null hypothesis was that there is no difference in fishing trips made to each zone. I assessed the similarity of all eligible fishing trips by 3 variables: net revenue from the sale of fish per trip (MYR $trip^{-1}$), where net revenue was calculated as revenue minus cost of fuel per trip; fish catch (kg $trip^{-1}$); and one way distance travelled from residence (km). Fishing trips with missing values for any one of the three variables were omitted from the analysis. The initial data set contained 1374 samples, as more than one fishing site was visited on some fishing trips. To reduce this data set for ease of presentation, I averaged variables by village of residence so that the final data set had 32 samples which were factored by fishing zone. One sample would thus be the averaged net revenue, fish catch, and distance from all fishing trips taken by fishers from village *x* to fishing zone *x*.

### 2.2.4 Flexibility index

To gauge fishers' flexibility in adapting to changes in access to fishing grounds, I assessed their responses to the following questions: 1) Would you travel further or to a different fishing ground if the price of petrol decreased?; 2) Would you travel further or to a different fishing ground if you had a bigger boat?; 3) Have you ever changed your fishing ground in response to observed changes in fish abundance?; 4) Do you have another job, or ever held another job besides fishing?

One point was allocated for every question that fishers responded 'Yes' to. Question 3 was preceded by a question earlier on in the interview that established whether fishers had experienced an increase, decrease, or no change in fish abundance in the past 5 years. I allocated one point to cases where fishers had experienced a decline in fish abundance and responded by moving to different fishing locations. The final flexibility score was a number between 0 and 1 that was the weighted average of each fisher's responses. Higher scores reflected more flexibility in adapting to spatial change, based on two hypothetical scenarios, fishers' past spatial responses to external impacts, as well as alternative livelihood opportunities. To assess patterns in fishers' responses to flexibility questions, I tested for differences in fishers' age, number of years fishing, and boat type (Table 2.3) using analysis of variance (ANOVA), while place of origin was tested using a chi-square test.

## 2.3 Results

### 2.3.1 Fishing trips

The data reported in this section are from catch logs. The majority of fishers used a variety of fishing gears and methods, with the exception of Kaligau fishers who almost exclusively used gillnets (Table 2.4). In contrast, Perpaduan fishers used a combination of 8 fishing gears and methods, while Damaran fishers were the only catch log participants who used crab nets. Cuttlefish prongs were used only during specific seasons, thus made up a small proportion of fishing trips. Multiple fishing gears and methods were used in all fishing zones (Table 2.5). It should be noted however, that within each zone were fishing locations that were gear specific. For example, waters around 30m deep in zone B were used mainly by hook and line fishers, or for jigging and trolling, whereas the shallower areas were shared with gillnetters, spear fishers, and free divers fishing for invertebrates; crab nets were used almost entirely within fishing zone E only (Table 2.5).

Fishers from Singgahmata, Maliangin, Damaran, and Kaligau tended to fish closer to home while fishers from Kobong, Perpaduan, and Lok Tohog travelled further. Maliangin fishers stayed closest to home, making fishing trips to locations that were on average just under 5km one way, while Lok Tohog fishers travelled five times further on fishing trips (Table 2.6). Fishers from 5 of the 7 participant villages made the most number of fishing trips to the fishing zone closest to and in which their village was situated (Table 2.7).

Fishers did not always fish in fishing zones that yielded the maximum average net revenue, where net revenue was computed as revenue from the sale of fish minus the cost of fuel (Table 2.7). Maximum net revenue zones were visited least by fishers from Maliangin, Perpaduan, and Singgahmata, with trip frequencies ranging from less than 1% to 8%. Only Kobong fishers fished at their maximum net revenue zone with some regularity, approximately 25% of the time. However, when net revenue was weighted in terms of distance travelled, I found that Damaran, Kaligau, Kobong and Perpaduan fishers did in fact fish most frequently in zones where their net revenue to travel distance ratio was maximized (Table 2.7). Surprisingly, fishers from Lok Tohog and Maliangin fished most frequently at fishing zones that yielded the lowest net revenue (and net revenue to distance ratio) (Table 2.7). Moreover, for Lok Tohog fishers, the minimum net revenue zone was also the one furthest away.

### 2.3.2 Preferred resource space

Fishing zones where fishers fished at least 65% of the time were considered to be preferred resource spaces (PRS). I based this on the assumption that a PRS encompasses fishers' top two preferred fishing zones, where higher preference is indicated by more fishing trips. I then calculated the proportion of trips that each catch log participant made to fishing zones A-G, and summed up each fisher's top two highest trip proportions. The 65% cut-off point was arrived at by finding the minimum of the summed proportions across all catch log participants.

Generally, preferred resource spaces occurred in the fishing zone closest to fishers' village of residence (Table 2.7). There was some overlap in the use of all fishing zones; fishing zones B and D had the most overlap, as all catch log participants fished there at least occasionally. The spatial delineation of PRS according to fishers' village of residence was verified by fishers' mental maps, where fishers from the same village generally identified the same fishing locations although they did not fish together as a group (Figure 2.2). A fisher's PRS was usually confined to one zone but could be spread over two or three zones.

All fishers demonstrated some degree of knowledge about their fishing environment. Their mental maps showed details about the type of habitat and fish that could be caught at different locations, with the level of detail varying from general descriptions such as "I usually catch *ikan batu* (demersal reef fish) here because there is a big *takat* (coral head) below" to accounts like:

> You have to go to {fishing ground A} early in the morning when the fish are hungry. There, we jig for *termanung* (*Atule mate*). After we have caught fish there, we go over to {fishing ground B} where it is deep and there are lots of big fish. At {fishing ground B} we will use the *termanung* as bait for catching *ikan putih* (*Caranx spp.*) with hook and line (Interview data, 2007).

### 2.3.3 Similarities in fishing zones

The pattern of fishers' spatial use was tested using one-way ANOSIM which indicated a significant difference between different fishing zones (p=0.012, R=0.175). The R value suggests that although significant, the difference between groups is slight and fishing zones are largely similar. Five pairwise ANOSIM tests had R values greater than the global R statistic, of which 4 were significant at the 0.05 level (Table 2.8). Zone E appeared to have most dissimilarity compared with other zones.

### 2.3.4 Perceptions of safety in fishing grounds

The following analysis is drawn from fisher interviews. Safety at sea was considered to be important or very important by all fishers, with none saying that safety was not an important factor in deciding where to fish. In describing their fishing routes, fishers generally focused on safety by tracing the most secure paths, using proximity to villages and army stations, as well as the positioning and shelter offered by small islands, as reference points. While the criteria for safe/unsafe location were consistent across villages, the locations that were considered to be safe/unsafe varied from village to village.

Fishing locations that fishers considered safe were those in their village 'zone', shallow and/or close to shore, or had army stationed nearby. On the other hand, fishers did not feel safe and tended to avoid fishing in locations that were too far away or had too many unfamiliar boats due to fear of being robbed at sea or stranded by rough sea conditions. Areas known or rumoured to be inhabited by crocodiles or sharks were also labelled as dangerous and unsafe for fishing. Several fishers who used gillnets identified shallow areas as being unsafe because their nets would get tangled or torn.

Seventy seven percent (n=74) of fishers perceived their village 'zone', 'nearby' places, or places 'in front of the village' as being safe for fishing. Fifteen percent identified locations between 10km to 20km away as being safe, while only 7% of fishers considered all fishing grounds to be safe for fishing. Of places that were perceived to be unsafe, 33% (n=72) was due to the spatial attribute 'far away', 21% was due to fear of 'pirates', and 14% was due to environmental factors such as rough sea conditions, deep waters, and crocodiles. Eight percent of fishers felt that there was no unsafe fishing locations, while 7% believed that there were unsafe places but did not know which places were unsafe.

Fishers typically fished at places that they considered to be safe. This was determined by cross-validating the spatial range marked on maps with fishing frequency at locations that fishers identified as being safe during interviews. Only 12% (n=72) of fishers continued to fish at a place that was considered to be dangerous. This behaviour was generally driven by fishers' belief that fish abundance was higher at the dangerous location.

### 2.3.5 Fishers' flexibility

Fishers' responses to each of the four questions relating to indicators of flexibility are presented in Figure 2.3. There was no significant difference in flexibility score by village of residence and number of years fishing. On the other hand, age made a difference, with fishers older than the median age of 39 having a higher average flexibility score of 0.4 compared to 0.3 for younger fishers ($F(1, 73)=4.64$, $p=0.03$, $\eta^2=0.06$). Fishing experience explained the difference between fishers who were willing to travel to different fishing locations and those who were not. Fishers who chose to change fishing location if petrol was cheaper had an average of 26 years of fishing experience compared to 19 years for those who were unwilling to change location ($F(1, 67)=6.11$, $p=0.02$, $\eta^2=0.084$), while for the bigger boat scenario it was fishers with 24 years of fishing experience compared to 18 years ($F(1, 67)=5.07$, $p=0.03$, $\eta^2=0.07$). Owning a boat with a bigger engine (>13hp) did not make a difference in whether fishers chose to change location under the bigger boat scenario. Place of origin influenced fishers' willingness to make spatial changes. The percentage of interviewees who had changed fishing grounds after a decline in fish abundance differed by place of origin, (chi-square=14.1, 1 d.f., $p<0.05$). Fishers who were born outside their current village of residence were those who had previously changed fishing grounds in response to a decline in fish abundance, while fishers who were born in their current village of residence tended not to have changed fishing grounds.

## 2.4 Discussion

Fishers in Sabah exhibit distinct spatial preferences which can affect their willingness to adapt to spatial regulations. These preferred resource spaces vary by fishers' home village- they are on average within 10 km of fishers' home villages, not connected to shore, and are typically perceived to be safe. On the other hand, PRS do not necessarily yield the highest catches or highest net revenue to fishers, but are still the destinations of between 65% and 96% of all fishing trips across villages.

The spatial range of Banggi fishers is comparable to those in artisanal fisheries in Spain and Indonesia (Piniella et al. 2007, Oostenbrugge et al. 2001), although in Nicaragua, fishers' spatial ranges extended up to 50km (Daw 2008a). The decision to fish near or far from fishers' residences is often framed as a trade-off between travel cost and expected profits, whereby economic incentives are thought to motivate fishers to extend their spatial ranges (Daw 2008a, Caddy and Carocci 1999). On the other hand, my results suggested that economic incentives may not be the only factor motivating fishers' spatial behaviour, as fishers generally fished less frequently at higher average net revenue zones that were far away from the village.

The preference to fish within a defined area may be influenced by fishers' preferred gear, and by the small size and low engine power of their boats (Piniella et al. 2007, Wiyono et al. 2006). However, these hypotheses are not supported by our results, given that multiple gears are used within a single zone, and fishers from the same village tended to fish in the same PRS regardless of whether they owned a wooden plank boat with a small inboard engine or a fibreglass boat with a more powerful outboard engine.

I propose that the departure in fishers' spatial choices may be explained by 'unobservable' factors such as perceptions, whereby unobservables may be "…the causal connection between past and future choices…" (Smith 2005). Below, I discuss the concept of mental maps as the manifestation of fishers' perceptions that shape the boundaries of preferred resource spaces and subsequent spatial behaviour.

### 2.4.1 Mental maps and fishers' preferred resource spaces

The extent of fishing grounds use as shown on fishers' mental maps matched closely with preferred resource spaces identified from catch log forms. Although I used prepared maps rather than hand drawn maps, verbal responses that accompanied these *defacto* mental maps still gave insight to personal preferences and use patterns that enabled me to sufficiently understand fishers' perspectives of the marine environment.

Maps from fishers of the same village tended to show similar fishing locations, while corresponding catch logs also revealed similar fishing patterns among fishers originating from the same village. This likely arises because mental maps are a communal entity (St. Martin 2001, McKenna et al. 2008), where knowledge of particular fishing spots are shared between kin and friends and passed on from father to son. I saw evidence of this in some villages where the majority of fishers belonged to the same ethnic group: Damaran fishers were primarily ethnic Balabac, and the only group from the catch log programme that regularly fished for crabs, which took place in zone E. This may account for the difference in zone E that showed up in ANOSIM pairwise tests.

Knowledge of fishing methods was also a communal entity. The predominantly Bajau fishers from Kaligau were the most specialized in gillnets, in contrast to most other villages in Banggi where fishers used multiple gears. In one part of Mabul in Semporna, the Suluks specialized in fishing for tuna, in contrast to other fishers who fished for multiple species. Finally, Ubians from Maliangin and Singgahmata were especially skilled and interested in trolling for Spanish mackerel.

The family ties and history associated with particular fishing grounds contributes to permanency and temporal stability in the use of those fishing grounds (Begossi 2006, McKenna et al. 2008). This may be why two fishers from Lok Tohog consistently travelled further than other fishers to fish - both were originally from a village on Balambangan, and despite having settled and raised families in Lok Tohog, preferred to return to their PRS in Zone E. Likewise, many Singgahmata fishers were originally from Maliangin and continue to travel back to Zone B to fish. Given that a particular community of fishers has invested much time and energy in the formation of detailed spatial knowledge of their marine environments, it is not unexpected that they would resist having to move beyond the boundaries of their mental maps and give up unique and therefore valuable fishing knowledge.

Issues of perceived safety are another example of an unobserved variable that was not quantified in catch logs. The majority of fishers in Banggi and Semporna associated safety with distance, in that places close to their residence were usually considered to be safe for fishing whereas there was high tendency to describe unsafe places as those being far away. Perceptions of danger, or the fear of danger, can overshadow rational behaviour (Poggie et al. 1976). In this study, fishers' perceptions may have accounted for voluntary avoidance of certain areas and subsequent delineation of fishing grounds. Fishers' high valuation of fishing zones that are safe, hence those that are closest to their village, is illustrated by the transformation of low net revenue generating fishing zones to maximum net revenue zones once distance has been factored in, and further confirmed by the fact that fishers from 4 out of 7 villages fish most frequently in zones where net revenue to distance ratio is maximized.

In low technology fisheries, mental maps act as fish finders and nautical charts. Some fishers' mental maps have been assessed to be ecologically and geographically accurate (McKenna et al. 2008), and are, in a sense, fishers' comparative advantage. If fisher went to places beyond their mental map boundaries, they would lose the advantage of their existing detailed knowledge base (Holland and Sutinen 2000, Begossi 2001), and have to extend the bounds and complexity of their mental maps. In developing any mental model of a complex natural system, simple rules are often employed (Berkes and Kislalioglu-Berkes 2009), and while they may not always represent the optimal solution, they do typically yield predictable results which increase the resilience of a low technology fishery. Furthermore, fishers are inclined to maintain their accustomed fishing patterns out of habit (Holland and Sutinen 2000), which reinforces their partiality towards preferred resource spaces.

### 2.4.2 External impacts

The lack of technology usage in Banggi and Semporna likely contributes to fishers' strong adherence to a PRS, given their reliance on mental maps alone. It can be argued that once technology is introduced, a fisher's mental map will be dramatically altered and fishers will be able to expand their spatial coverage to search for fish as well as expand the methods for tracking fishing success and profitability. Indeed, the introduction of GPS was shown to change fishers' spatial behaviour (Daw 2008a), and the availability of sonar caused the mental maps of older fishers to be dismissed by newer generation of fishers in Norway (Eythorsson 1993). Similarly, the introduction of mobile phones in Kerala enabled fishers to check market prices at different ports, which resulted in some fishers travelling further to obtain better prices (Foss and Couclelis 2009). On the other hand, McKenna et al. (2008) found that devices such as GPS and echo sounders were used more for safety and spot fixing by Lough Neagh fishers in Ireland, and did not replace the in-depth ecological and biophysical knowledge of mental maps.

### 2.4.3 Fishers' flexibility

Fishers' flexibility provides an indication of how they are likely to respond to external pressures, such as a change in economic or ecological conditions. I would expect fishers who have made spatial adjustments in the past, or those who have a positive attitude towards changing their spatial behaviour (i.e. higher flexibility), to have more capacity for spatial adaptation outside of their PRS.

My results indicated that older fishers, and those with more years of fishing experience, were more willing to adjust their spatial fishing behaviour. This situation may arise as older, more experienced fishers have built up a deeper pool of knowledge which younger fishers lack. Further, it is reasonable that fishers who changed fishing locations in response to perceived decline in fish abundance tended to be those who originated from outside their current village of residence. As such, they were already inclined to make spatial adaptations.

Only the scenario involving the use of bigger boats elicited a positive response to adjusting spatial use from the majority of fishers. Fishers who elaborated on this decision made reference to mother boat operations, which are typically owned by commercial fish traders. Mother boats tow the boats of 4 to 6 small-scale fishers to distant fishing grounds, where the fishers fish consecutively for between 4 to 10 days before returning home. In this context, fishers do not have to rely on their mental maps to find suitable locations to fish. Furthermore, going out in a bigger boat with other crew usually implies safety in numbers as well as more protection from rough sea conditions (Poggie et al. 1976). With safety concerns and perceptual constraints removed, fishers appear willing to make different spatial choices, under conditions where there is little risk and/or loss to them.

Conversely, lower petrol costs and fishing in degraded conditions, whereby fishers have experienced decreased catches for at least the past 5 years, did not incite fishers to change their spatial habits or preferences. Only 34% of fishers were positive towards making spatial changes (travelling further or going to another fishing zone) if the price of petrol decreased. This is surprising since fuel cost is typically the largest cost component for small-scale fishers (Teh et al. 2007, Daw 2008a), and the main trade-off in travel distance. However, it is consistent with the result that only fishers from one village fished where they maximized their net revenue. In explaining their choice, safety emerged as the primary consideration, as fishers were not willing to travel further or to different locations due to fear of piracy, mechanical failure, and rough sea conditions. Again, this is consistent with the result that fishers in fact maximized their net revenue if distance was factored into the calculation. Then, fishers actually tended to fish in zones where their net revenue to distance ratio was maximized, that is, preferred locations were those that were closer and hence perceived to be safe.

## 2.5 Management implications

The finding that fishers fish within a preferred resource space is similarly observed in other fisheries, where fishing patterns and spatial choices remain stable through time (Holland and Sutinen 2000, Begossi 2006). However, less attention has focused on small-scale fishers' ability and willingness to fish beyond their preferred resource space. My results caution against spatial regulations created on the assumption that displaced fishing effort can be readily redistributed.

The demarcation of preferred resource spaces suggests that the 'openness' of marine resources varies according to whose eyes they are viewed from. This raises the important point that resource use should be understood from local perspectives (Burke 2001), as fishers' perceptions impart spatial heterogeneity on the marine environment that is seldom recognised by managers (St. Martin 2001). At the same time, spatial constraints only persist for those who perceive them. This can lead to unequal impacts on local fishers as compared to outsider fishers to whom the resource base may appear truly 'open', especially since spatial decisions are often made based on aggregated fishing effort and catch data that do not correspond with the scale at which local fishers fish.

My findings show that unobservable elements like perceptions drive diversity in spatial preferences among fishers so that lumping fishers as one homogenous stakeholder group will not capture the dynamics of resource use adequately (Holland and Sutinen 2000). This is reflected in the distinct preferred resource spaces of fishers from different villages, such that closure of a particular area has the potential to affect one group of fishers disproportionately. Spatial preferences can also be highly localised, such as in Banggi, where fishers from two villages, Singgahmata and Perpaduan, that are located less than 2 km apart, showed differences in their spatial allocation of fishing effort. Rather than the conventional approach of designating no take zones, management can accommodate preferred resource spaces by designating areas where fishing is allowed, so that at least one PRS for each village remains accessible to fishers. The sense of legitimacy that this approach fosters among resident fishers can lead to higher user compliance (Kuperan and Sutinen 1998, Hatcher et al. 2000, Hønneland 2000). In the event that the PRS of fishers in Banggi and Semporna are earmarked for closure, management can ease fishers' transition to new fishing grounds by appealing to their sense of security through ensuring that those new areas are free from pirates. In addition, alternative grounds should be within sight of familiar landmarks for fishers to orient themselves in space.

More generally, this chapter makes the case for conducting spatial management at a scale that is congruent with the scale at which local users 'see' their resources (St. Martin 2004). This increases the ability to detect unobservable factors that may otherwise be masked by other more obvious and measurable variables. My results also indicate the necessity to augment existing data sets with human perceptional data, particularly in many small-scale fisheries where managers' eagerness to adopt more scientific, biologically driven spatial planning methods risks sidelining fishers' perceptions even further.

I have demonstrated that mapping fishers' PRS can be a low-cost yet effective method to get to the root of 'unobservables' that influence fishers' spatial behaviour as well as their responses to spatial intervention. Such a perspective is absent from much of fisheries management, especially in small-scale fisheries in developing countries where fishers tend to be socially and economically marginalized in the first place. Integrating fishers' perceptions can lead to more socially acceptable initiatives, and ultimately help to attain sustainable fisheries management objectives.

**Table 2.1.** Number of fishers by village of residence who participated in the catch log programme in cycle 1 (May-July 2007), cycle 2 (November 2007), cycle 3 (February 2008), and cycle 4 (September 2008). The number of filled catch logs is listed in brackets.

| Cycle | Damaran | Kaligau | Kobong | Lok Tohog | Maliangin | Perpaduan | Singgahmata |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 4 | 3 | 2 | 4 | 5 | 4 |
| (353) | | (41) | (46) | (17) | (99) | (75) | (74) |
| 2 | 1 | 2 | 2 | 1 | 4 | 3 | 2 |
| (253) | (22) | (49) | (38) | (8) | (47) | (41) | (48) |
| 3 | 2 | 0 | 3 | 0 | 4 | 3 | 4 |
| (272) | (48) | | (38) | | (66) | (53) | (67) |
| 4 | 3 | 2 | 2 | 0 | 6 | 4 | 2 |
| (329) | (74) | (49) | (45) | | (77) | (45) | (39) |

**Table 2.2.** Characteristics of fishing zones used by Banggi catch log participants. Boundaries were defined by L. Teh, while gear and user data are from catch logs. TR=fish trap; JIG=jigging; FD=free dive; SP=spear; HL=handline; GN=gill net; LL=longline; TRL=trolling; CP=cuttlefish prong; CN=crab net.

| | | | Fishing gears and methods | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zone | Estimated area ($km^2$) | Defining boundaries | TR | JIG | FD | SP | HL | GN | LL | TRL | CP | CN | Dominant users |
| A | 26 | From Patanunan Island in the west to Balak Balak Island in the east | x | x | x | x | x | x | x | x | x | | Perpaduan, Kaligau |
| B | 15 | West of Maliangin Besar Island, encompassing Maliangin Kecil Island and bounded in the southwest by navigation buoy | x | x | x | x | x | x | x | x | | | Maliangin, Singgahmata, Perpaduan |
| C | 9 | On the east side of Maliangin Besar Island, encompassing Lingisan and extending to Wak Wak Bay | x | x | | x | x | x | | x | | | Singgahmata |
| D | 6 | Nearshore waters bounded approximately by Kobong in the south and Limbuak in the north | x | x | x | x | x | x | | x | x | x | Kobong, Kaligau |
| E | 32 | Area encompassing Teluk Lung and Simuanguak Island | x | x | | x | x | x | | x | | x | Damaran, Lok Tohog, Kobong |
| F | 5 | The west side of Malawali Island | x | x | | | x | x | x | x | | | Singgahmata, Perpaduan |
| G | 17 | Area encompassing Kuambang reef and extending towards the southern edge of Sibogo Islands | x | | | x | x | x | x | x | | | Perpaduan |

**Table 2.3.** Summary of interview data on fishers' demographics and boat type by village.

| Village | Average age | Average no. of yrs fishing | % of fishers born in current village of residence | Boat type | Boat material |
|---|---|---|---|---|---|
| **Banggi** | | | | | |
| Batu Sireh | 39 | 22 | 90 | 13 hp inboard engines, range 7-22 hp | wood |
| Damaran | 35 | 15 | 100 | 7 hp inboard engines | wood |
| Dogoton | 41 | 21 | 100 | 7 hp inboard engines | wood |
| Maligu | 49 | 22 | 100 | Mix of 6-7 hp inboard engines and 15-20 hp outboard engines | wood and fibreglass |
| Malawali | 40 | 24 | 100 | 6 hp inboard engines | wood |
| Sibogo Air | 38 | 16 | 67 | 6 hp inboard engines | wood |
| Sibogo Balak | 35 | 20 | 86 | 6-7hp inboard engines | wood |
| **Semporna** | | | | | |
| Dinawan | 47 | 35 | 17 | Range 7-33 hp inboard engines, one outboard engine | wood |
| Hampalan Laut | 36 | 22 | 100 | Majority no engines, range 6-13 hp inboard engines | wood |
| Mabul | 36 | 18 | 11 | 40 hp outboard engines and 7 hp inboard engines | wood |
| Omadal | 51 | 27 | 100 | Range 3.5-10 hp outboard engines | wood |

**Table 2.4.** The percentage frequency (%) at which catch log participants in Banggi use different fishing gears and methods, where fishers are categorized by their village of residence. Frequency is calculated as the number of times a fishing gear is used over four catch log cycles.

| Village | Trap | Jigging | Free dive | Spear | Handline | Gillnet | Crab net | Long line | Cuttlefish prong | Trolling |
|---|---|---|---|---|---|---|---|---|---|---|
| Damaran | 0 | 3 | 0 | 2 | 11 | 35 | 49 | 0 | 0 | 1 |
| Kaligau | 0 | 0 | 0 | 0 | 0 | 96 | 0 | 0 | 2 | 0 |
| Kobong | 15 | 7 | 0 | 38 | 30 | 1 | 0 | 0 | 0 | 6 |
| Lok Tohog | 66 | 3 | 0 | 17 | 14 | 0 | 0 | 0 | 0 | 0 |
| Maliangin | 6 | 33 | 1 | 9 | 34 | 5 | 0 | 0 | 0 | 12 |
| Perpaduan | 33 | 9 | 6 | 15 | 20 | 1 | 0 | 6 | 0 | 10 |
| Singgahmata | 0 | 23 | 0 | 0 | 43 | 0 | 0 | 0 | 0 | 35 |

**Table 2.5.** The percentage frequency (%) at which fishing gears and methods are used by catch log participants at fishing zones in Banggi. Frequency is calculated as the number of times a fishing gear is used over four catch log cycles.

| Zone | Trap | Jigging | Free dive | Spear | Handline | Gillnet | Crab net | Long line | Cuttlefish prong | Trolling |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 35 | 10 | 0 | 5 | 19 | 18 | 0 | 5 | 0 | 8 |
| B | 6 | 24 | 5 | 12 | 31 | 5 | 0 | 0 | 0 | 17 |
| C | 6 | 19 | 0 | 15 | 31 | 2 | 0 | 0 | 0 | 27 |
| D | 3 | 13 | 3 | 22 | 16 | 21 | 2 | 0 | 1 | 15 |
| E | 21 | 4 | 0 | 14 | 15 | 17 | 27 | 0 | 0 | 1 |
| F | 29 | 2 | 0 | 26 | 29 | 0 | 0 | 10 | 0 | 4 |
| G | 28 | 0 | 0 | 14 | 23 | 0 | 0 | 22 | 0 | 13 |

**Table 2.6.** One way distances (km) travelled from catch log participants' village of residence in Banggi to fishing locations, based on daily fishing trips recorded by fishers over four cycles.

| Village | Minimum | Maximum | Average |
|---|---|---|---|
| Damaran | 4 | 25 | 15 |
| Kaligau | 2 | 38 | 9 |
| Kobong | 2 | 40 | 13 |
| Lok Tohog | 3 | 37 | 26 |
| Maliangin | 2 | 10 | 5 |
| Perpaduan | 1 | 31 | 9 |
| Singgahmata | 2 | 48 | 9 |

**Table 2.7.** Summary of average net revenue earned by catch log participants at each fishing zone, and average one way distances travelled to each zone. Zones that are in bold are the preferred resource space (PRS) of each village. An asterisk marks the zone within which the village is situated.

| Village | Zone | Average net revenue (MYR/trip) | Average distance (km) | Net revenue to distance ratio | Trip frequency (%) |
|---|---|---|---|---|---|
| Damaran | B | 7 | 23 | 0.3 | 5 |
| | **E*** | 31 | 13 | 2.4 | 82 |
| | D | 34 | 14 | 2.4 | 13 |
| Kaligau | C | 13 | 13 | 1.0 | 1 |
| | B | 33 | 18 | 1.9 | 8 |
| | **A*** | 33 | 5 | 7.0 | 65 |
| | D | 34 | 17 | 2.1 | 23 |
| | E | 82 | 33 | 2.5 | 3 |
| Kobong | C | 40 | 4 | 11 | 1 |
| | **D*** | 41 | 3 | 15 | 46 |
| | **B** | 43 | 10 | 4.3 | 27 |
| | A | 43 | 6 | 7.3 | 2 |
| | E | 69 | 29 | 2.4 | 24 |
| Lok Tohog | **E** | 13 | 24 | 0.6 | 86 |
| | D* | 34 | 3 | 11 | 4 |
| | B | 40 | 10 | 3.9 | 11 |
| Maliangin | **B*** | 26 | 4 | 5.8 | 96 |
| | D | 44 | 7 | 5.9 | 2 |
| | C | 72 | 3 | 23 | 1 |
| Perpaduan | C | 8 | 6 | 1.5 | 1 |
| | **B** | 27 | 10 | 2.6 | 33 |
| | **A*** | 53 | 4 | 12 | 47 |
| | D | 84 | 7 | 11 | 4 |
| | G | 85 | 23 | 3.8 | 7 |
| | F | 95 | 21 | 4.6 | 8 |
| Singgahmata | G | 7 | 19 | 0.4 | 1 |
| | C | 24 | 6 | 4.2 | 12 |
| | D | 27 | 9 | 3.2 | 8 |
| | **B** | 27 | 9 | 3.0 | 65 |
| | A* | 27 | 8 | 3.5 | 10 |
| | E | 35 | 48 | 0.7 | 0 |
| | F | 42 | 15 | 2.9 | 3 |

**Table 2.8.** Results of one-way ANOSIM test comparing fishing trips across 7 fishing zones. Pairwise tests with R values greater than the global R are listed. The global test had 999 permutations and pairwise tests had 3 to 999 permutations. Significance was set at p=0.05.

| | R value | p value |
|---|---|---|
| Global test | 0.175 | 0.012 |
| Pairwise tests | | |
| A,E | 0.409 | 0.038 |
| B,E | 0.338 | 0.016 |
| C,D | 0.199 | 0.064 |
| C,E | 0.336 | 0.032 |
| D,E | 0.36 | 0.008 |

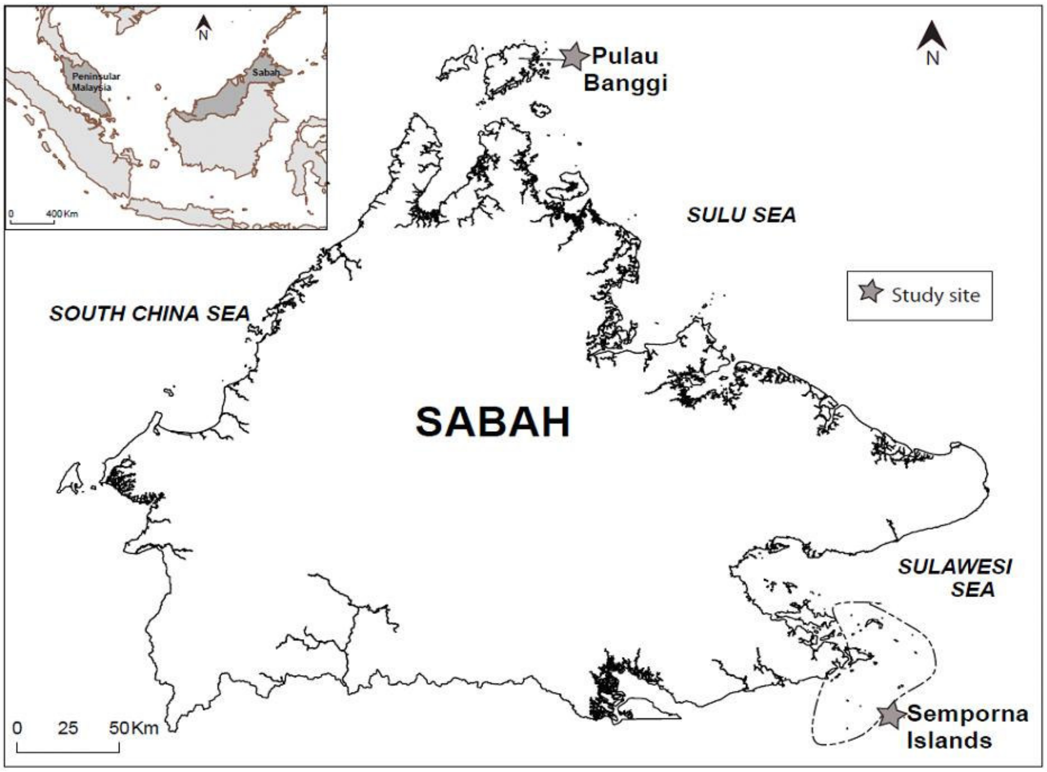


**Figure 2.1.** Map showing the main study sites of Pulau Banggi and Semporna islands in Sabah, Malaysia.

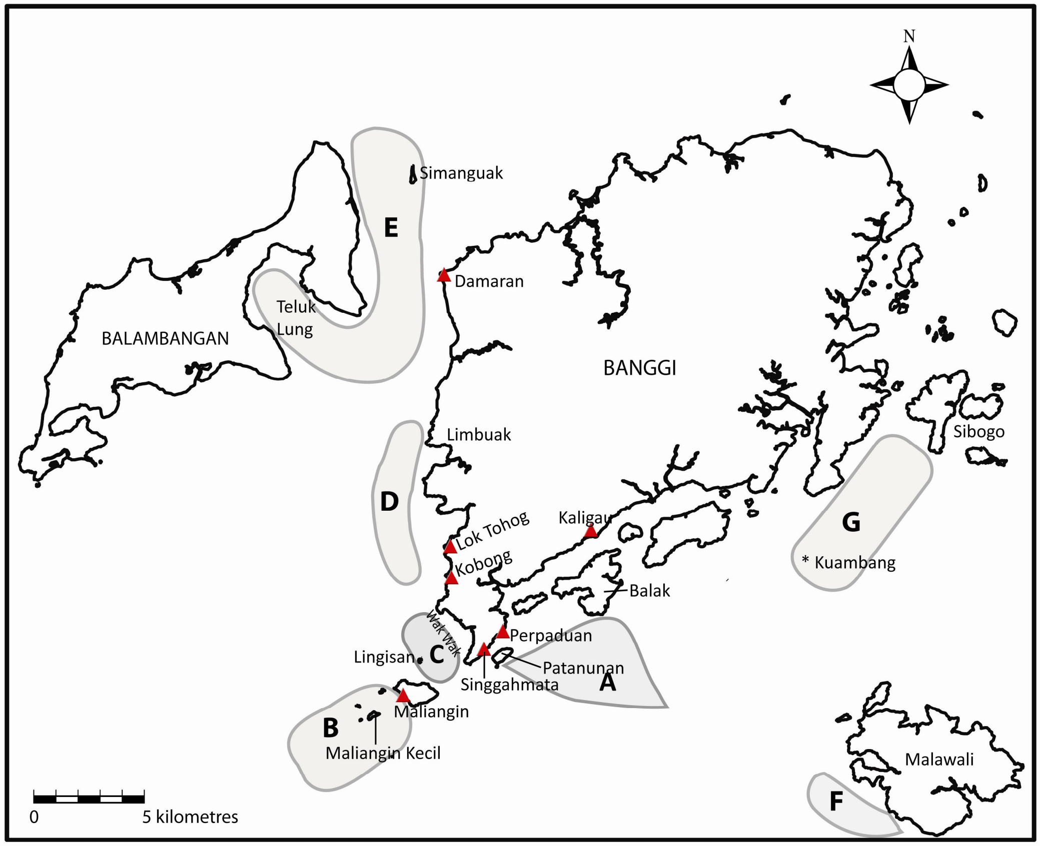


**Figure 2.2.** Areas in Banggi that are used by catch log participants for fishing (zones A to G). The marked zones are the aggregated fishing areas of individual fishing locations identified by fishers on their mental maps. Villages of catch log participants are marked by triangles.

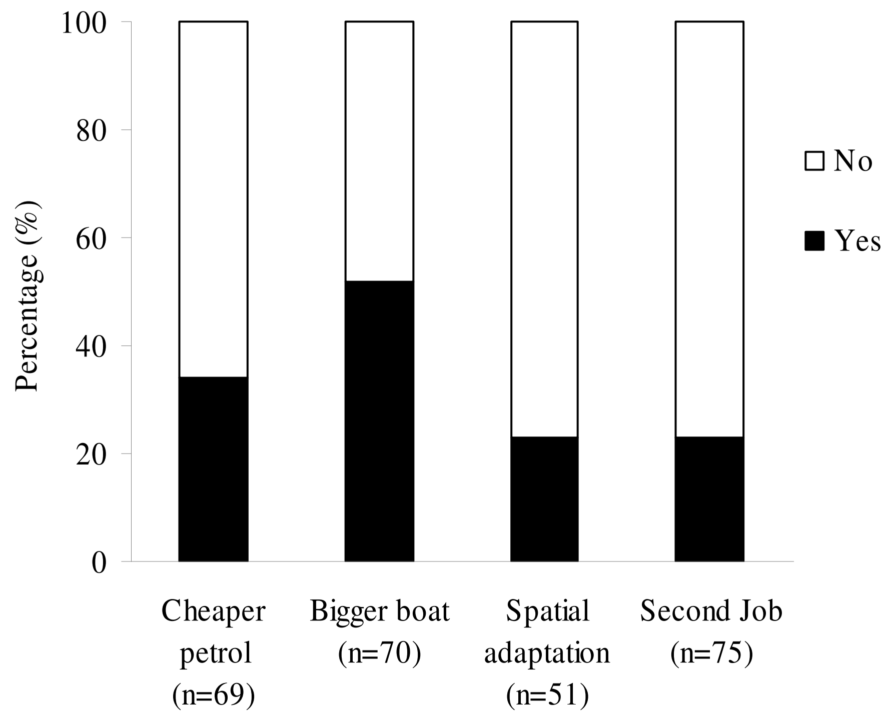


**Figure 2.3.** Proportion of fishers' responses to 4 indicator questions of flexibility. 'Cheaper petrol' and 'Bigger boat' are scenarios of whether fishers would travel to a different fishing location given the respective circumstances. 'Spatial adaptation' refers to whether fishers have previously changed their fishing grounds in response to perceived fish abundance decline, and 'Second job' refers to whether fishers have a job other than fishing.

# Chapter 3: Integrating human dimensions to marine spatial management using a fuzzy logic approach

## 3.1 Introduction

Spatial regulations are a core component of managing fishing effort, and are especially pertinent for marine protected areas (MPAs) that are increasingly being used for addressing fisheries, in addition to biodiversity conservation issues. I define MPA as multiple-use marine areas that include protected zones as well as zones for extractive use. Effective spatial management involves striking a balance between conserving biological resources and accommodating multiple uses of the resource base (Francis et al. 2002, Dalton et al. 2010). As such, site selection and zoning of marine areas should ideally not only achieve conservation targets, but also motivate compliant behaviour from resource users, a factor that has tended to be missing from previous attempts to designate MPA areas (Kritzer 2004).

Engaging affected users in the early stages of development is an essential step in MPA designation and contributes to MPA success where they have occurred (ole-MoiYoi 2003, Lundquist and Granek 2005, Mwaipopo 2008). An earlier attempt to incorporate the human dimension into an MPA site selection and performance algorithm employed a statistical ordination technique (Alder et al. 2002). Marxan, a popular marine reserve design software, also accommodates human values by representing foregone fisheries catch, revenue, and other socio-economic benefits as costs, wherein the optimization algorithm seeks to achieve biodiversity targets at the lowest possible cost. Nevertheless, the prevailing sentiment prioritises biological over socio-economic considerations during site evaluation (Roberts et al. 2003), and social considerations are inadvertently side-lined (Kritzer 2004). Even when stakeholder views are integrated in spatial planning, they are usually done so after an initial biological model has been developed (Stewart and Possingham 2005). Subsequently, the role that human decisions and behaviour ('human dimensions') play in affecting the outcome of fisheries and MPA management efforts is commonly overlooked (Mascia 2003).

Omitting human dimensions from marine spatial planning may prompt poor user compliance that can cancel out benefits arising from an MPA (Jameson et al. 2002, Botsford et al. 2003, Claudet and Guidetti 2010), and undermine attaining fisheries and/or conservation objectives (Kelleher et al. 1995, Sethi and Hilborn 2008). Successful spatial management is therefore tied closely to encouraging appropriate human behaviour and gaining the support of communities that are impacted by the regulations (Walmsley and White 2003). We not only have to consider what types of biological outcomes are desired, but also plan for what sort of human responses are preferable (Charles and Wilson 2009). Thus, I argue that marine spatial planning methods have to adopt a more inclusive evaluation framework, one that recognises the role of humans in the marine environment, if they are to be practical for future applications.

I propose an alternative approach, consisting of a fuzzy logic expert system that combines fishers' spatial preferences with biological criteria, to assess site suitability for protection. I will outline the structure of this fuzzy expert system and apply a prototype of the model to a small-scale fishery in Sabah, Malaysia, that is currently in the process of being gazetted as a multi-use MPA.

### 3.1.1 Background

Incorporating human dimensions to spatial planning requires a management decision support tool that can:

i) Integrate qualitative and quantitative variables;

ii) Deal with approximations and imprecision inherent in human judgement; and

iii) Be intuitive, easy to use, and engaging for both managers and stakeholders.

These criteria are not well met by existing mathematical models or geographical information systems used for marine spatial planning, which tend to be embedded within a traditional Boolean logic operating system. Boolean logic reduces assertions of reality to being either true or false statements, with no mechanism for accommodating varying degrees of truth and their associated uncertainty. As such, it is fundamentally mismatched for modelling the way humans reason and for representing the continuous nature of the marine environment.

Fisher spatial allocation is typically analysed and modelled from disciplinary perspectives, such as economics based profit maximization theory (Hilborn and Kennedy 1992, Robinson and Pascoe 1997), or ecology based foraging theory (Swain and Wade 2003, Abernethy et al. 2007, Bertrand et al. 2007). These approaches tend to include select variables that are measurable and considered relevant by managers, but may not match with stakeholders' objectives or priorities. Consequently, model outputs do not always fully explain certain aspects of fishers' behaviour (Béné and Tewfik 2001, Guest 2003, Salas and Gaertner 2004, Abernethy et al. 2007).

Fuzzy logic presents a viable alternative. Fuzzy logic is a way of dealing with reasoning that is approximate rather than precise, through the use of linguistic terms to embody uncertainty (Eierdanz et al. 2008). Essentially, fuzzy logic permits a gradual transition from one category to the next, as opposed to the rigid class boundaries imposed by Boolean logic. The use of natural language allows users to frame qualitative variables in a format that is conducive for quantitative analysis. It also accommodates imprecision through simple and intuitive linguistic modifiers like 'somewhat' and 'a little', therefore is well suited for describing the often non-linear relationship among and between influencing variables and fishers' spatial preferences.

The basis of fuzzy logic models is fuzzy set theory, which allows variables to assume a degree of membership in one or more fuzzy sets. A variable's membership in a fuzzy set is defined by a membership function, and can be interpreted as its possibility of association with that particular set, expressed as a value between 0 and 1. In contrast, variables in crisp (binary) sets either belong to a set, or do not belong, with full certainty. Fuzzy logic thus provides the mechanism for handling qualitative, human dimension variables, which are seldom represented in existing site selection and zoning tools.

## 3.2 A fuzzy logic expert system for marine spatial management

My proposed fuzzy logic expert system is an index of site suitability for protection, which I will term the protected area suitability index (PASI) (Figure 3.1). The PASI was programmed in Visual Basic (VBA) in Excel 2003, using coding adapted from Cheung (2007). I define site suitability as the degree to which a marine site is suitable to be zoned for protection, that is, closed to extractive uses, based on its conservation value (higher value=higher suitability) and status as a preferred resource space by fishers (lower preference=higher suitability).

The input data are attributes of the site that is selected for assessment. Spatial attributes consist of fisher preference variables and conservation variables. The fisher preference subcomponent includes the input variables fish catch (kg $trip^{-1}$), net revenue (MYR $trip^{-1}$), distance from nearest village (km), water depth (m), and crowding (number of boats). Input variables to the conservation subcomponent are endangered species occurrence (scale of 1-10), hard coral cover (%), and fish abundance (number ($100m^{-2}$). The two subcomponents are then weighted to arrive at the final suitability score. The output is a score corresponding to four categories that describe the assessed unit's suitability for protection (i.e., closure) - Very high, high, moderate, and low.

A preferred resource space is one that fishers use persistently through time. The rationale for selecting sites that are not preferred resource spaces is guided by the principle that successful implementation of spatial regulations relies on creating conditions that facilitate compliant behaviour. Fishers tend to fish at places where they have in-depth knowledge about local ecological and environmental conditions (St. Martin 2001, McKenna et al. 2008). Furthermore, fishers tend to maintain accustomed fishing habits (Holland and Sutinen 2000), and there is high spatial and temporal stability in the use of fishing grounds by artisanal fishers (Begossi 2006). Thus, given a choice, fishers would rather fish in their existing, preferred fishing grounds than at new places where they have no pre-acquired knowledge. As such, from a human dimension perspective, it is logical to choose to protect sites where fishers or other users *do not* go, whether due to technological or social barriers, as this will increase the likelihood of a compliant response.

From an ecological perspective, a general rule of thumb for siting marine reserves is to avoid areas that are frequently used by humans, or are subject to natural disturbances (Botsford et al. 2003). For example, places where heavy fishing pressure has caused physical damage that is too extensive for habitat recovery would not be appropriate for protection (Roberts et al. 2003). Both human dimension and ecological principles guide the development of the PASI.

I next outline four stages of development in the PASI: knowledge input, fuzzification, inference modelling, and defuzzification (Eierdanz et al. 2008). I will explain how each stage of the development process works in the context of the coral reef fisheries of Banggi.

### 3.2.1 Knowledge input

I selected input variables that quantify or measure site suitability based on fishers' preferences and conservation value. The unique aspect of PASI is its ability to define 'suitability' from fishers' perspectives. This was accomplished by choosing variables which fishers themselves identified as being relevant and important to their spatial decision-making, such as the conditions that characterise a preferred fishing site. Conservation variables were selected according to criteria for assessing and siting marine reserves (Botsford et al. 2003, Roberts et al. 2003).

**Data types**

PASI input data were collected from semi-structured interviews and catch logs as outlined in Section 2.1.1. Below, I explain how data were collected and treated for input to the PASI.

Catch and net revenue – Data for these two attributes were extracted from catch logs and interviews. Location specific catch and net revenue data from catch logs were summed and averaged across the total number of fishing trips that were taken to each fishing location. Average catch and net revenue reported by fishers in interviews were first allocated to the fishing location(s) that each fisher identified as being a regular fishing location. When more than one fishing location was identified, I allocated catch and net revenue based on the percentage frequency with which each fisher used a particular site. Frequency information was reported by fishers, usually as the number of times a fishing location was visited per week. The final catch and net revenue input for assessed sites in the PASI was the averaged catch and net revenue of all fishers at one site. There was no significant difference in catch and net revenue reported by each method; therefore I combined both sets of data.

Net revenue per trip was calculated as revenue from selling fish minus the cost of fuel per trip. I assumed that the opportunity cost of labour was zero, due to the limited options in Banggi for sustained employment in other sectors, and fishers' tendency to prefer a fishing lifestyle. Hence, the cost component in calculating net revenue did not include labour.

Distance - Distance was measured as the one way distance (km) from individual fishing locations to the closest village using the ruler tool in Google Earth.

Depth – Depth information was largely derived from fishers' knowledge. Where this was not available, I obtained the approximate depth from nautical charts of the region. I made the assumption that depth from fishers' knowledge was comparable to that from nautical charts, although I acknowledge that this is not always the case. Depth readings from nautical charts show the depth of the area at low tide, while fishers' judgment of depth may be affected by their fishing technique and gear.

Crowding – Crowding data came from interviews, and was defined as the number of boats that a fisher sees fishing in the same area, where 'area' is that within sight. I also relied on personal observations of fishing boats that were encountered during fishing grounds surveys taken intermittently in 2004, 2005, 2007, and 2009.

Endangered species – Sighting frequency was based on fisher interviews, personal observations from 2004-2009, informal conversation with local residents and researchers, and secondary data (e.g., The Star Online 2009, Rajamani and Marsh 2010). The endangered species I asked about included marine turtles, dugongs, dolphins, sharks, and whales. All fishers knew what each species looked like, except for a few who confused dolphins and whales. Fishers reported whether they had ever seen an endangered species in their regular fishing locations, then gave an indication of how often sightings were. Sighing was reported in number of times per week, per month, or per year. Due to the high variability in responses, I converted reported sightings for each species into the qualitative categories 'seldom', 'sometimes', and 'often'. I then mapped these categories onto a scale from 1 to 10, with 10 being very often, and averaged the frequency scores of each species. Thus, for each site, I had between 0 to 5 frequency scores, one for each species, from which I selected the maximum score as the final input value to the PASI. I used the maximum score to reflect high importance on conserving an area for endangered species, regardless of how many or what type of endangered species was present.

Coral cover and fish abundance - Data were compiled from underwater surveys conducted by a conservation organization in 2000-2002 (Harding et al. 2001) and one research institution on separate occasions in 2002, 2003, and 2004 (Koh et al. 2002, Lee and Chou 2003, Tanzil and Chou 2004). All underwater surveys followed the Reef Check method (www.reefcheck.org), from which I extracted percentage hard coral cover and fish count per $100m^2$. I matched PASI test sites to the closest available underwater survey site.

### 3.2.2 Fuzzification

Fuzzification is the process of transforming input in crisp form into linguistic categories. This transformation is facilitated by membership functions that map the input to their respective categories with an associated degree of membership. The degree of membership ranges between 0 and 1, and can be thought of as the possibility of 'belonging' to a certain category. Therefore, one input can belong to one or more linguistic categories, each with a different degree of membership. Membership functions can be many forms, such as triangular, trapezoidal, or S shaped (logistic growth), of which appropriate selection is dependent on one's understanding of the variable that is being transformed. Since I had no knowledge of the behaviour of the variables, I chose trapezoid and triangle shapes, which are the simplest functions, to allocate PASI variables to their linguistic categories (Table 3.1).

Values that depict the boundaries of linguistic categories for PASI attributes, and how these relate to site suitability outcomes, are listed on Table 3.2. Linguistic categories for fisher spatial preference variables could be discerned directly from fishers' perceptions of their marine environment. For instance, I asked fishers what depth they considered to be 'deep' or 'shallow', and fishers were free to define depth in any unit (e.g. metres, feet, fathom, length of anchor rope). I then collated all the depths of fishing grounds that fishers fished at, as well as the corresponding descriptive attribute of that depth. The qualitative descriptions formed the linguistic categories, and the range of fishers' responses determined the maximum and minimum bounds (the 'input space') for each category. The same procedure was used for fuzzifying distance and crowding variables (Figure 3.2).

Two approaches were used to fuzzify the fish catch and net revenue variables. The first approach relied on interview responses as described above. In the second approach, I calculated quartiles of fish catch and profit distributions from 1078 catch log records. I then used these intervals to guide the formation of linguistic categories. For example, very high profit membership included input ranging between the third and fourth (maximum) quartiles. The second approach allowed me to create category boundaries that were objective, thereby providing a check to ensure that model parameterisation was consistent with fishers' actual earnings and fish catches. Finally, I compared the categories obtained using the two approaches, and where required, adjusted the intervals to best reflect on the ground reality from fishers' perspectives.

The boundaries for endangered species were arbitrarily defined on a scale from 1 to 10. Hard coral cover fuzzy membership sets were based on ASEAN-Australian Living Coastal Resources project coral cover scale (Chou 1994)- Poor (<25%), fair (25% to 50%), good (>50% to 75%), and excellent (>75%)- with overlaps of 5% on either side of each category to account for accuracy and precision limitations associated with coral cover sampling methods (Nadon and Stirling 2006). Fish abundance fuzzy membership sets were defined from the upper and lower quartiles of fish abundance distributions from underwater fish visual census in Banggi and Semporna (Koh et al. 2002, Lee and Chou 2003, Tanzil and Chou 2004; Ho and Kassem 2010).

### 3.2.3 Inference modelling

The inference engine for the fuzzy logic model contains sets of heuristic rules that govern how the PASI behaves. Essentially, these heuristic rules govern the problem solving process; Rules are written in 'IF…THEN' form, and contain two parts- an antecedent (existing condition) and a conclusion. A confidence factor between 0 and 1 is attached to each rule, whereby the confidence factor reflects fishers', managers', or stakeholders' belief in the strength of the expressed outcome. Alternatively, the confidence factor can also be used to reflect the relative importance of a particular rule to the final suitability outcome.

Fuzzified inputs (antecedent) trigger relevant rules that reach a conclusion about the level of site suitability for protection. The output of each rule forms a fuzzy set with associated degree of membership being stipulated by the membership function. A threshold level that defines the minimum acceptable degree of membership can be used to filter out antecedents with very low degrees of possibility. In the PASI, the minimum threshold level is set at 0.2, so fuzzified inputs that do not satisfy this level will not trigger heuristic rules.

#### Rationale for heuristic rules

The rationale for heuristic rules was based on theories and empirical research of how fishers allocate their fishing effort spatially, as well as guiding principles for representing biodiversity in marine protected areas. Rules in the fisher preference subcomponent were based on the principle of protecting places where fishers do not fish, in order to minimize the negative impacts of MPA creation. Hence, higher preference for a site infers lower suitability for protection (Table 3.3). In addition to fishers' own stated preferences, I used fishing frequency as an indicator of preference, such that a location that was visited frequently was more preferred to another location that was less frequently visited.

I tried to design the PASI to 'behave' like fishers - interviews revealed fishers' conceptualization of interactions in the marine environment, such as the association of deep water with big and more fish. These mental concepts were then converted into rules of thumb on spatial preference. For example, the aforementioned association resulted in the heuristic rule 'If depth is deep then fisher preference is high and site suitability is low'. Catch log data provided further information on fishers' resource use patterns, which were then used to design heuristic rules that better reflected actual behaviour, as opposed to basing rules on theoretical assumptions alone.

**Catch, net revenue and fisher preference**

Fishers are conventionally treated as rational decision makers driven by financial incentives to fish where expected profit/ benefit is maximized (Robinson and Pascoe 1997). Therefore, a site with higher catch or net revenue is more preferred (hence less suitable for protection). Heuristic rules describing catch, net revenue, and suitability outcomes maintained this positive relationship between expected benefit and effort allocation given the large amount of literature supporting this view. At the same time, empirical evidence from catch logs suggested that fishers did not make spatial choices that maximized either catch or net revenue alone (Chapter 2). Rather, fishers tended to allocate effort to where the ratio of net revenue to distance travelled was maximized (Chapter 2). I accommodated this behaviour with the qualifying condition that suitability becomes *higher* if the distance that fishers have to travel to the fishing site is *very far*.

**Depth and fisher preference**

Deeper sites were more preferred over shallow sites by most fishers because of an association of deep places with bigger and more fish. Based on interviews, 67% of fishers stated that they preferred to fish in deep places versus 18% who preferred shallow, 11% who liked both depths, and 4% who had no preference (n=73). There was a tendency for gillnet and spear fishers to prefer shallower sites, but very shallow areas that were connected to shore tended to be avoided.

At the same time, most fishers were wary of very deep places due to fear of sharks and concern for personal safety. Thus, I established highest preference for sites that were little deep and deep, while very deep sites had the least preference.

**Distance and fisher preference**

Fishers displayed an overwhelming preference for fishing in places that were close rather than far. This was supported by catch log data, which showed that on average 76% of daily fishing trips were taken to fishing sites that were on average 9 km one way from the home village, although some fishers stayed as close as within 4 km. The maximum distance travelled one way on a day fishing trip was 40km, and made up only 2.4% of all logged fishing trips. Near was associated with safety, which all fishers (n=75) stated as being an important or very important factor in their daily fishing decision. Therefore, I established very high fisher preference for sites that were near to villages and low preference for sites that were far from villages. In addition, the strong influence of distance on fishers' decisions was such that I lowered fishers' preference for a site with very high average catch or net revenue if the site was very far away from a village.

**Crowding and fisher preference**

The rule for crowding was based on fishers' aversion to fishing in places with many people. Fishers preferred locations with few boats because of the perception that the presence of many fishers scared fish away. However, the implications of this rule were ambiguous - if preference for crowded sites was low and suitability high, then in fact crowded places would be more suitable for protection. Yet, this contradicts the overarching principle of protecting sites where fishers do not go.

**Biodiversity and protection suitability**

Heuristic rules in the conservation subcomponent were based on MPA design criteria such as maximizing habitat heterogeneity and protecting rare and endemic species (Botsford et al. 2003, Roberts et al. 2003). Sites with higher values of endangered species, coral cover, and fish abundance were considered more suitable for protection.

### 3.2.4 Defuzzification

Defuzzification conflates the fuzzy sets from all the rules to one final fuzzy set and transforms it back to a single point output in crisp form (i.e., the suitability score). Rules that lead to the same conclusion are collected, weighted by their assigned certainty factor, and then combined using the MYCIN method (Buchanan and Shortliffe 1984). MYCIN was originally developed for making medical diagnoses; it accumulates incremental pieces of knowledge (symptoms) to decide on a likely outcome (disease).

The result of this aggregation is a final fuzzy set expressing site suitability, which is then defuzzified using the centroid weighted average method. Essentially, this method finds the centre of gravity of the area covered by the shape of the final fuzzy set, which is created by superimposing the fuzzy sets from all the rules together (Figure 3.3).

## 3.3 PASI results

I applied a prototype of the PASI to assess the suitability of a fishing site in Banggi, which I will call FG1, for protection and closure to fishing. The input values to the model are FG1's spatial attributes -depth, distance to nearest village, catch, net revenue, crowding, threatened species occurrence, hard coral cover, and fish abundance. For example, FG1 has a depth of 24m, which belonged to the fuzzy sets 'deep' with a degree of membership (d.m.) of 0.8. On average, fishers caught 6kg of fish and earned MYR34[1] in net revenue for every trip they took to FG1, which corresponded to the fuzzy sets 'moderate' catch with d.m. of 0.25 and, the fuzzy sets 'medium' and 'high' net revenue with d.m. of 0.4 and 0.27 respectively. Heuristic rules relating each characteristic to a suitability outcome were activated. For example, a fish abundance count of 45 belonging to the fuzzy set 'good' with d.m. of 0.4 activated the rule 'If fish abundance is good then suitability is high'. The conclusions from running each rule were then aggregated to produce fuzzy sets for site suitability outcomes in the categories 'low', 'moderate', 'high', and 'very high'; the degrees of membership associated with each of these outcomes were 0.28, 0.5, 0.15, and 0, respectively. The range of outcomes for site suitability was defuzzified and produced a final suitability score of 3.9 for FG1.

## 3.4 Discussion

I propose a fuzzy logic expert system that explicitly accounts for human dimensions and conservation variables in identifying marine areas for protection from fishing. Fuzzy logic is used quite extensively in spatial applications, from evaluating potential sites for aquaculture

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[1] 1MYR=0.33USD, as of January 31, 2011.

(Tarunamulia 2008) to prospecting for minerals (Nykänen et al. 2008). ArcGIS, a leading geographic information system software, recently introduced fuzzy membership and fuzzy overlay options for spatial operations (ESRI 2010). Fuzzy logic thus has a solid foundation in spatial applications.

I demonstrated how the protected area suitability index (PASI) works. The suitability score of 3.9 indicates that despite positive conservation value, FG1 is only slightly adequate for closure due to high fisher preference. Although FG1 is characterised by moderate CATCH, its relatively high net revenue yield suggests that it is a good spot for catching commercially valuable fish species, hence fishers' preference for FG1.

The importance of engaging stakeholder participation in MPA design, and more broadly in conservation planning, is well recognised (Fernandes et al. 2005, Lundqvist and Granek 2005). In Marxan, setting criteria such as minimising revenue losses or opportunity costs of protection (Smith et al. 2009) is a way to reflect stakeholders' priorities. However, these criteria have to be defined in Marxan terms, through the use of boundary length modifier values and planning unit costs. The concept of these parameters is not easy to grasp for the general public, and likely fails to fully capture stakeholders' perspectives. Despite this shortcoming, a Marxan model that was developed with fisher input produced a more effective marine reserve design compared to another with no fisher input (Klein et al. 2008a). Arguably then, the use of more compatible language that is able to embody human dimensions should lead to even more effective solutions.

Fuzzy logic is that compatible language- it describes the system being modelled in linguistic terms that are both intuitive and straightforward. For example, fuzzy membership sets in the PASI are categorised according to fishers' terms. This not only simplifies the design procedure, but also makes the model more transparent since all assumptions that govern the fuzzy logic expert system are explicitly stated via heuristic rules. This is a definite advantage for enhancing communication with non-specialists (Smith et al. 2009). Simplicity and transparency also eliminate the need for incessant model 'tweaking', a task that is usually unavoidable while operating more complex mathematical models, but which can compromise the replicability and integrity of result outcomes (Loos 2006). The use of natural language also allows a range of views and rules to be combined to govern how the model operates, and ensures that one disciplinary perspective does not dominate. Overall, it can minimise the risk of disagreements among stakeholders (Eierdanz et al. 2008) that may stall the planning process.

In the real world, fishers' fishing decisions are influenced by their experiences, knowledge, and perceptions of biological and social features in the marine environment (Cordell 1974, Feinberg et al. 2003). This complexity is handled in the PASI, which accounts for preferred fishing sites by evaluating spatial attributes that are important to fishers, measuring how those spatial attributes are perceived by fishers, and anticipating how fishers act upon those perceptions. Ultimately, a multi-disciplinary approach such as this should help to realistically anticipate fishers' behaviour, hence facilitate effective planning and implementation.

Human experience is integral to producing a spatial zoning plan that works, and 'on the ground' knowledge is often more valuable than reserve-design software (Fernandes et al. 2005). Many researchers view local ecological knowledge as a legitimate alternative and complement to scientific knowledge (Berkes et al. 2000, Johannes et al. 2000, Aswani and Lauer 2006), but the qualitative and descriptive nature of local ecological knowledge has prevented it from being widely used outside the social sciences (Johannes and Neis 2007). In the PASI, I used fuzzy logic to integrate fishers' environmental knowledge in determining site suitability for protection. Others have used fuzzy logic to incorporate local ecological knowledge for stock assessment (Mackinson 2001) and to rebuild historical abundance estimates of a fishery (Moody 2008). Thus, fuzzy logic is capable of bridging the crucial gap between the social and quantitative fields.

Uncertainty over resource users' behaviour is a major hurdle in fisheries management that can potentially compromise conservation or sustainability goals (Fulton et al. 2011). Adaptive management aims to mitigate uncertainty over the long-term through a cycle of monitoring, learning, and adjusting (Allan and Stankey 2009). The PASI's flexible structure lends itself to incorporating this iterative process. As results emerge and feedback is gathered, system variables and rules can be updated to integrate new knowledge and changing conditions. For example, introduction of new technology may lead to the expansion of preferred resource spaces: fuzzy membership sets for distance can be reclassified, heuristic rules altered to reflect greater willingness, hence preference, for travelling further distances, and confidence factors adjusted to account for uncertainty in the system.

Although simple, the advantage of the PASI is its flexibility. Assessment sites do not have to conform to any pre-defined map grid or planning unit dimension; rather, each site can be any size or shape that is most amenable to the situation being considered. For example, an assessment site can be a local fishing ground, a spawning ground, or the complete range of a unique habitat. This mitigates distortions in over or under representing spatial features, a situation that may arise in models that require units of space to contain a value, regardless of whether or not that unit of space is significant to the overall system. It also overcomes scale issues that, depending on the spatial resolution of the data and planning units that is used, can affect the priority areas that are identified (Richardson et al. 2006, Shriner et al. 2006).

While I have specifically defined site suitability in terms of appropriateness for protection, the definition itself can be adapted to align with different management objectives. Similarly, while I have concentrated on fishers specifically, the concept of the PASI can readily be extended to integrate the interests of other resource users. As such, I think that the PASI will have wide applicability in many fisheries systems, especially small-scale fisheries in data-poor countries where lack of data may otherwise stall or delay decision-making.

In summary, a fuzzy logic approach to spatial management can address social aspects of marine resource use, the omission of which has contributed to the poor performance of many MPAs. Zoning sites to fulfill fisheries management or conservation objectives has to move away from a heavy focus on optimising biological targets towards more fully accommodating human uses of the marine environment. My proposed fuzzy logic based site selection decision support tool undertakes this task. Firstly, it provides an enabling mechanism to combine qualitative and quantitative variables in assessing a site’s suitability for protection. Secondly, fuzzy sets enable users to classify variables into linguistic categories, a capability that addresses vagueness and uncertainty inherent in trying to represent reality in a model. Thirdly, the fuzzy logic expert system operates using logic that is more similar to how humans reason. Combined, these qualities result in a spatial management decision support tool that stands out for its ability to explicitly incorporate human behavioural dynamics in assessing site suitability.

A fuzzy site selection expert system will be especially beneficial and have wide applicability in small-scale fisheries in developing countries, where humans interact closely with the marine environment. In such locales, the need to stem exploitative pressure is urgent, yet data and financial shortages preclude the practical application of technically demanding and data intensive models. Given its existing use in a range of spatial applications, it is logical to extend the many advantages of fuzzy logic towards marine spatial management.

**Table 3.1.** The shape of triangle and trapezoid membership functions, where *x* is the range of values of the data set. The base of the triangle is defined by *a* and *c*, while that of a trapezoid is defined by *a* and *d.* Maximum membership is achieved between *b* and *c* of a trapezoid, and at the peak of the triangle in a triangular function.

| Membership | Triangle | Trapezoid |
|---|---|---|
| 0 | $x \leq a, x \geq c$ | $x \leq a, x \geq d$ |
| $x - a/(b-a)$ | $a < x < b$ | $a < x < b$ |
| $(c - x) / (c - b)$ | $b \leq x \leq c$ | |
| 1 | | $b \leq x < c$ |
| $(d - x) / (d - c)$ | | $c \leq x < d$ |

**Table 3.2.** The numerical boundaries used to define categories of fuzzy membership sets and how membership categories relate to site suitability outcomes. 'X' indicates a shift to a higher suitability outcome under the condition of 'Distance is Very Far'.

| Attribute | Category | Final suitability outcome | | | |
|---|---|---|---|---|---|
| | | Low | Moderate | High | Very high |
| Catch (C) | Low | | | C<5 | C<5 |
| (kg trip$^{-1}$) | Moderate | | 4<C<18 | **X** | |
| | High | C>15 | **X** | | |
| Crowding (Cr) | Few | Cr<6 | | | |
| (no. of boats) | Moderate | | 5<Cr≤15 | | |
| | Many | | | 8<Cr<30 | 8<Cr<30 |
| Depth (Dp) | Shallow | | | Dp<7 | |
| (m) | Little deep | 5<Dp≤12 | | | |
| | Deep | 10<Dp≤40 | 10<Dp≤40 | | |
| | Very deep | | | | 35<Dp<60 |
| Distance (Dt) | Very near | Dt<3 | | | |
| (km) | Near | 2<Dt≤8 | | | |
| | Far | | 7<Dt≤18 | 7<Dt≤18 | |
| | Very far | | | | Dt >15 |
| Net revenue (NR) | Low | | | | NR<20 |
| (MYR trip$^{-1}$) | Medium | | 15<NR≤40 | | |
| | High | 30<NR≤60 | | **X** | |
| | Very high | NR>55 | **X** | | |
| Endangered | Seldom | 1<ES<3 | | | |
| Species (ES) (1-10) | Sometimes | | 2.5<ES≤7 | 2.5<ES≤7 | |
| | Often | | | | 6<ES<10 |
| Coral cover (CC) | Poor | CC<25 | | | |
| (%) | Fair | | 20<CC≤55 | | |
| | Good | | | 45<CC≤75 | |
| | Excellent | | | | CC>70 |
| Fish abundance (FA) | Poor | FA<20 | | | |
| (no. 100m$^{-2}$) | Fair | | 12<FA≤45 | | |
| | Good | | | 35<FA≤75 | |
| | Excellent | | | | FA>70 |

**Table 3.3.** Evidence supporting and opposing the relationship between fisheries and biophysical attributes and effort allocation (i-iv); biodiversity indicators and site protection suitability (v-vii). I make the assumption that higher effort allocation implies higher preference for a site, and that preference and protection suitability are inversely related (denoted in brackets).

| Attribute | Direction of relationship | | Supporting | Opposing |
|---|---|---|---|---|
| | Preference | Protection suitability | | |
| i. Catch, net revenue | + | (-) | 2,3,6,7,8,9, 13,14,5,17,23,20 | 1,4,10,11,16,18, 19 |
| ii. Distance | - | (+) | 12,21,22,23 | |
| iii. Depth | + | (-) | Interviews | |
| iv. Crowding | - | (+) | 5, interviews | 4 |
| v. Endangered species | | + | 15,24,25 | |
| vi. Coral cover | | + | 15,24,25 | |
| vii. Fish abundance | | + | 15,24,25 | |

References: 1. Salas and Charles (2007), 2. Portier et al. (1997), 3. Bertrand et al. (2004), 4. Holland and Sutinen (2000), 5. Vignaux (1996), 6. Eales and Wilen (1986), 7. Hilborn and Ledbetter (1979), 8. Healey and Morris (1992), 9. Gillis et al. (1993), 10. Pet-Soede et al. (2001), 11. Van Oostenbrugge et al. (2001), 12. Sampson (1992), 13. Marchal et al. (2007), 14. Dupont (1993), 15. Roberts et al. (2003), 16. Abernethy et al. (2007), 17. Aswani and Lauer (2006), 18. Guest (2003), 19. Béné and Tewfik (2001), 20. Robinson and Pascoe (1997), 21. Caddy and Carocci (1999), 22. Abernethy et al. (2010), 23. Forcada et al. (2010), 24. Botsford et al. (2003), 25. Halpern (2003)

**Table 3.4.** Attributes of FG1 in southeastern Banggi. Each input is assigned to its appropriate fuzzy membership set with associated degree of membership (d.m).

| Attribute | Input value | Fuzzy membership set (d.m) |
|---|---|---|
| Depth (m) | 24 | Deep (0.8) |
| Distance (km) | 7 | Near (0.33) |
| Average catch per unit effort (kg $trip^{-1}$) | 6 | Moderate (0.25) |
| Average net revenue (MYR $trip^{-1}$) | 34 | Medium (0.4), High (0.27) |
| Average crowding (no. of boats) | 6 | Moderate (0.5) |
| Endangered species occurrence (1-10) | 7 | Sometimes (0.25); Often (0.11) |
| Hard coral cover (%) | 46 | Fair (0.45); Good (0.08) |
| Fish abundance (no. $100m^{-2}$) | 45 | Good (0.4) |

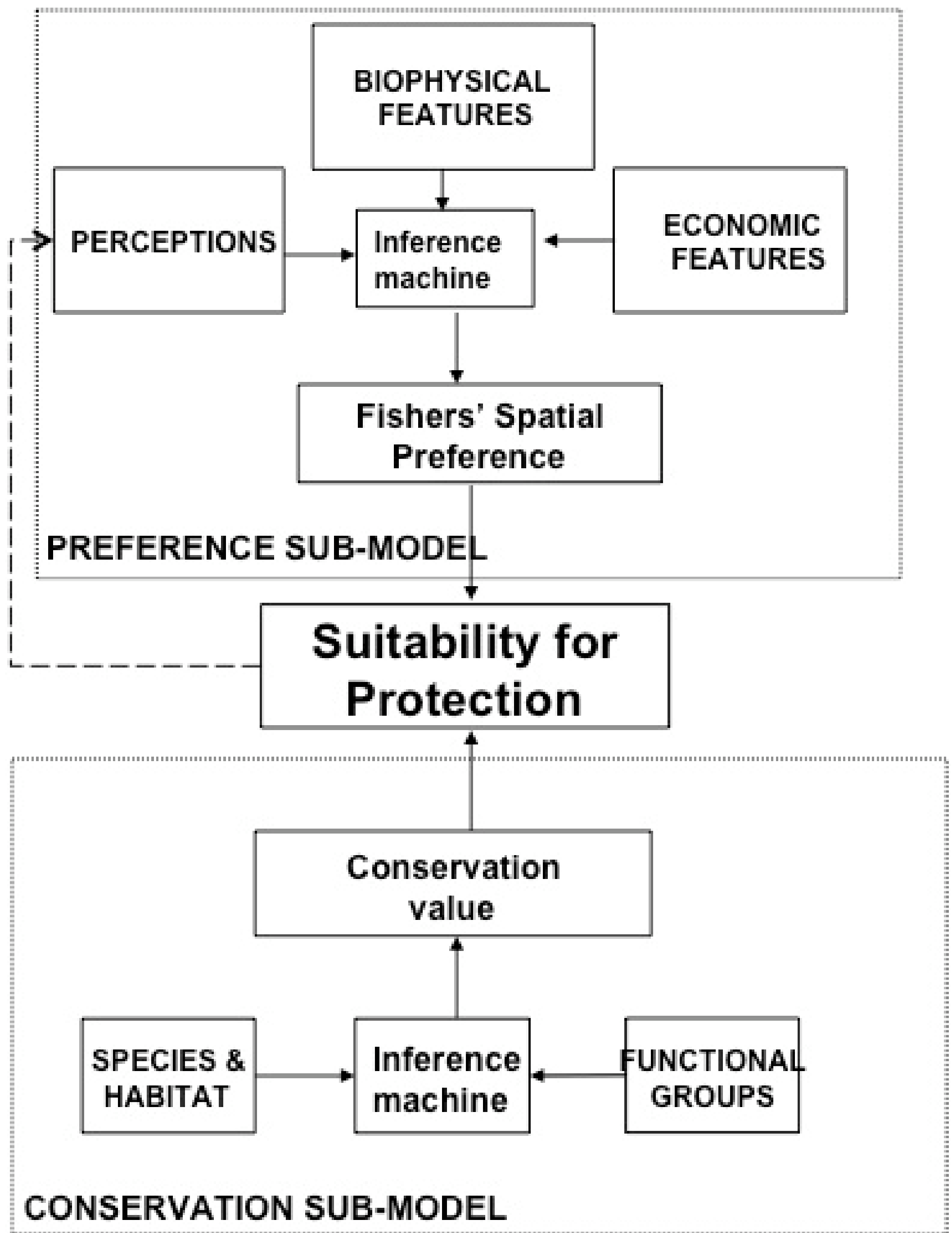


**Figure 3.1.** Schematic diagram of the PASI (protected area suitability index).

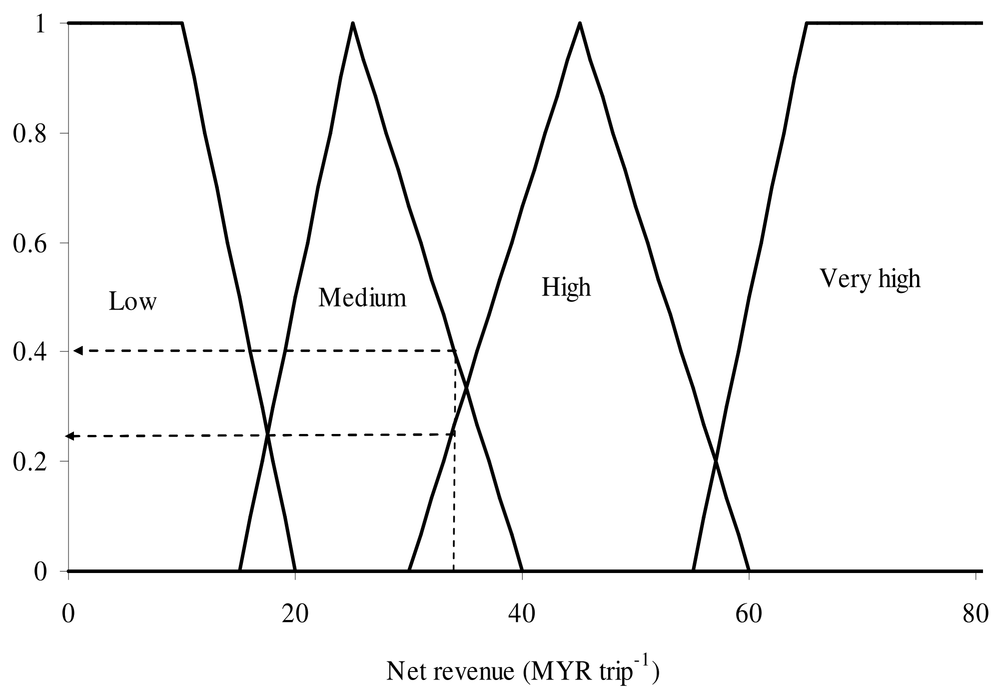


**Figure 3.2.** Fuzzy membership sets for the spatial attribute ‘net revenue’. A site that yields average net revenue of MYR34 per trip (indicated by dotted line) would belong to the fuzzy set ‘medium’ and ‘high’ with 0.4 and 0.27 degrees of membership respectively.

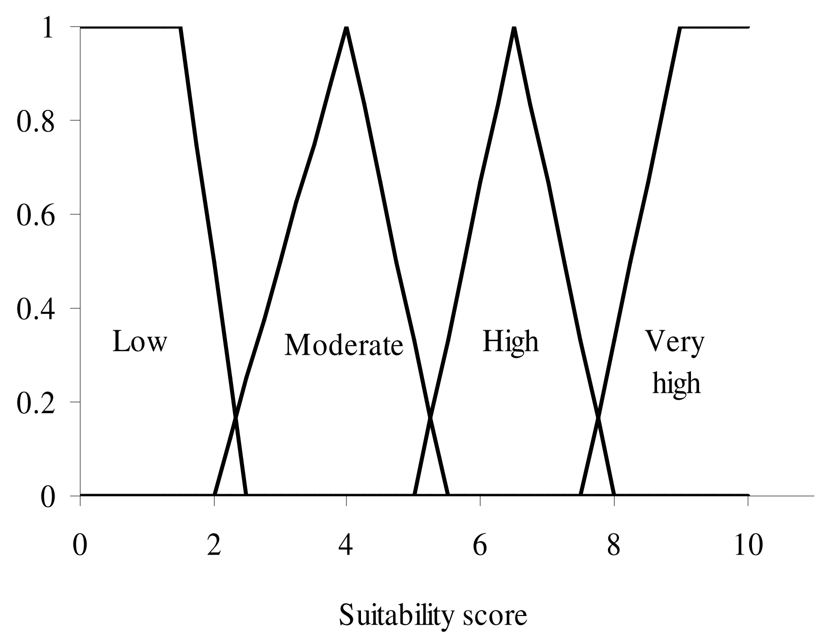


**Figure 3.3.** Fuzzy sets for site suitability outcomes, where suitability is scored on a scale from 0 to 10.

# Chapter 4: A tool for site prioritisation of marine protected areas under data poor conditions

## 4.1 Introduction

In many developing countries, Marine Protected Areas (MPA) are used as a way to demonstrate the benefits of conservation and to build local community participation in, and support for conservation initiatives (Leisher et al. 2007). MPAs range from no-take marine reserves to multi-use managed areas; in this paper, I refer primarily to multi-use MPAs where provisions are made for both extractive and non-extractive activities. Empirical evidence suggests that MPAs can help to recover fish biomass (Russ and Alcala 2004, McClanahan et al. 2007, Goñi et al. 2008) and in some cases improve the socio-economic condition of communities that live near MPAs (Mwaipopo 2008, Govan 2009, Unsworth et al. 2010). On the other hand, the creation of MPAs can also lead to conflict and non-compliant behaviour (Gambino et al. 2003, Christie 2004, McClanahan et al. 2005). The ecological effectiveness of MPAs depends on how well fishers adhere and adapt their fishing effort to new protected area boundaries (Dinmore et al. 2003, Forcada et al. 2010). Placing protected zones where they can achieve biodiversity objectives and win community support is thus crucial for a successful MPA.

Zoning is the backbone of MPA design processes, whereby marine areas are spatially delineated for specific uses. The process of selecting sites for protection can be a costly and long process (Hansen et al. 2011). In the past, political motivations pushed the creation of many MPAs, but increasingly systematic planning, where management objectives and stakeholder needs are explicitly laid out and addressed (Agardy 1997), is the preferred approach (Villa et al. 2002).

A number of spatially explicit decision support tools have emerged to aid the systematic placement and zoning of MPAs. Of these, Marxan is arguably one of the more popular. It uses an optimization routine to evaluate trade-offs and to select sites that meet specified conservation targets and that are complementary to one another. Others such as MarineMap and Ecotrust's Open OceanMap are GIS interfaces that facilitate spatial management by visually representing multiple uses of the marine ecosystem. A GIS based multi-criteria analysis framework was used to zone a multi-stakeholder driven MPA (Villa et al. 2002). Alternatively, Ecospace software (spatially explicit whole ecosystem simulations) can be applied to zoning problems, whereby the ecological and fisheries effects of placing a protected zone are evaluated (Varkey 2010).

The main drawback to currently available tools for systematic MPA zoning is that they require moderate to heavy investment in time, expertise and funds for data collection, monitoring, and training (Sale 2008). This is not practical for developing countries which tend to be limited in all these aspects. Furthermore, prevailing high fishing pressure in many of these countries instills a sense of urgency to create protected areas. Under such conditions, common sense and expert knowledge may provide better guidance than a poorly constructed model. In fact, experience has shown that an opportunistic approach to marine reserve placement fared no worse than systematic planning in places where there was lack of data, money, and technical resources to undertake rigorous site selection analysis (Hansen et al. 2011).

Stakeholder preferences are one of the key factors to consider during site selection, as they increase the likelihood of zoning places that attain community support and longevity in the long term (Lundquist and Granek 2005, McClanahan et al. 2005, Mwaipopo 2008). Existing systematic planning tools can and do integrate stakeholder preferences, albeit in an indirect way. For example, socio-economic data were used as a cost metric in a Marxan model to select the least cost solution for a network of protected areas in California (Klein et al. 2008b). More recently, the development of Marxan with zones enabled practitioners to set targets for the exclusion of fishing grounds from being selected into protected zones (Grantham and Possingham 2010). Despite these efforts, ecological processes and targets remain the focus of most marine zoning processes (Roberts et al. 2003). The level and quality of socio-economic data and understanding of stakeholder preference is still poor compared to the amount and understanding of the natural science component (Klein et al. 2008b), leading to results that may be biased in favour of the better represented side.

I see a gap in current marine spatial management approaches, as few are ideally suited for the needs of developing country fisheries. Here, humans, in particular fishers, are an integral part of the marine ecosystem and their spatial use patterns have to be understood. Developing country fishers' resource use spaces tend to coincide with areas of high biodiversity, which in many cases, are poorly documented. Finally, the people in charge of managing the marine ecosystem in these regions often do not have the time or technical and financial resources to collect data and commit to lengthy model building exercises.

In Chapter 3, I proposed the PASI as an alternative spatial management support tool which is practical for data poor conditions – one that makes use of best available data, is adaptable to different scales, and is not time consuming to operate. The PASI assesses site attributes by fishers' preferences as well as conservation value, so that results balance the need to mitigate impact on users and to protect biodiversity at the same time. I assume that fishers will fish in places with attributes that are desirable from their points of view. These preferred resource spaces are then considered to be less suitable for inclusion in protected zones. This chapter will concentrate on the robustness of the model, using a case study of a proposed multi-use MPA in Sabah, Malaysia.

## 4.2 Methods

### 4.2.1 Input data to the PASI

I conduct a sensitivity analysis using data from Banggi, Sabah. Banggi is currently in the process of being zoned a multi-use MPA. A detailed site description can be found in Chapter 2.1.1. I assign a confidence factor of 0.5 to all rules, and allocate equal weightings of 0.5 to the fisher preference and conservation subcomponents. This means that both subcomponents contribute equally to the final suitability score. Finally, I set the minimum threshold level at 0.2.

I also conduct a comparative analysis of Banggi sites with no-fishing sites in the Sugud Islands Marine Conservation Area (SIMCA). SIMCA is a no-take marine reserve that was created in 2001 and whose boundaries are regularly patrolled by an enforcement team. It is located in Sandakan district south of Banggi and north of Semporna. Endangered species such as green and hawksbill turtles are frequently seen within SIMCA (Chung 2008), as are several species of sharks, rays, and dolphins. Whalesharks are sighted during some years in the first quarter of the year. Valuable commercial fish species such as barramundi cod, humphead wrasse, and groupers, snappers, and trevallies are also common in several sites within SIMCA (Teh et al. 2008, Reef Guardian, unpublished data).

I compiled data on 18 known fishing locations in Banggi, Sabah, as well as 11 dive sites that are closed to fishing in the Sugud Island Marine Conservation Area (SIMCA) (Table 4.1). SIMCA biodiversity data were from underwater surveys conducted in 2009 by SIMCA research staff, using fish belt transects and line intercept transects for benthic communities (Reef Guardian, unpublished data). The occurrence of endangered species was based on my observations from over 100 dives in the SIMCA, as well as observations and anecdotes from SIMCA research staff and other divers. The depth at which underwater surveys were conducted was used as the depth input. There was no fisheries data input for SIMCA, as all sites were closed to fishing; I assumed that fish catch and net revenue were 0. The closest fishing villages to SIMCA were located between 20 and 30km to the west and southwest of assessment sites, where distance was measured using the ruler function in Google earth. Crowding was minimal (1-2 boats), or zero, as despite a fishing ban in SIMCA, commercial boats were sometimes found fishing within the protected area. The typical reason for infringement was unawareness of SIMCA boundaries. Banggi data came from two sets of empirical data as well as secondary sources (Table 4.2). The two sources of empirical data were catch logs and interviews.

### 4.2.2 Sensitivity analysis

I tested the reliability of the PASI's structure and its results. To test the PASI's structure, I used a data set that consisted of 100 simulated sites with randomly generated numbers because of the limited availability of real sites with complete data. Random numbers were defined to fall between the minimum and upper quartile of each attribute subset, except for the attributes endangered species, coral cover, and fish abundance, in which the range was between the minimum and maximum values of each attribute subset. I generated random numbers with a normal distribution to obtain representation of the range of values in the domain of each subset. To test the reliability of the PASI's results, I used 18 sites in Banggi with complete data sets to evaluate how sensitive the system was to losing information. I did not use the 11 SIMCA sites because I did not want results to be potentially confounded by the 0 catch and net revenue values in SIMCA sites.

First, for both structure and results robustness, I assessed the influence of individual attributes on the system by removing one attribute at a time and measuring the deviation of outputs and percentage change from the original values (1.1a, 1.1b). Small deviations indicate that no one attribute had an overriding impact on the output, and hence demonstrate that the PASI system is robust.

$\text{Dev} = S_{a\text{-}i} - S_a$ (1.1a)

$\Delta = (S_{a\text{-}i} - S_a)/ S_a$ (1.1b)

where Dev and $\Delta$ are deviation and percentage change respectively, *S* is the estimated suitability score, *a* is the data set with all attributes, and *a-i* is data set with attribute *i* removed.

A second test of the PASI's structural robustness was the systematic removal of increasing numbers of randomly selected attributes until only one attribute was left. Deviation from the baseline was measured after each attribute was removed. I repeated this removal of increasing numbers of attributes 50 times, and report the median of the deviations.

Robustness of the PASI's results was assessed by systematically turning off one rule at a time and measuring the deviation in estimated suitability scores. The magnitude of deviations from the baseline can thus alert us to particular rules that have a disproportionately large influence on the result outcomes. Lastly, I tested how sensitive the PASI was to different threshold values by measuring the deviation as I varied the threshold level from 0.1 to 0.9.

### 4.2.3 Verification of suitability scores

I investigated the validity of the PASI by comparing similarities in estimated suitability scores between 18 sites in Banggi and 11 sites in SIMCA. I scaled estimated suitability scores to two anchor points, the worst and best case scenarios under the range of conditions in the PASI. All 18 Banggi sites were actively used fishing grounds. SIMCA sites were within a strictly no-take reserve created in 2001, therefore I expected higher suitability scores for SIMCA sites. I applied a one way ANOVA to test the null hypothesis that there was no difference in suitability scores between sites in Banggi and SIMCA.

## 4.3 Results

The PASI estimated the suitability of 18 sites in Banggi and 11 sites in SIMCA, Sabah, for protection. The average total suitability score for Banggi sites was 3.8 (where a score of 10 is maximum suitability for protection), with lower and upper bounds of 2.8 and 4.9 respectively

(Fig. 1). Overall, Banggi suitability scores for the preference subcomponent averaged 3.0, which was lower than the average conservation subcomponent score of 4.6. The average total suitability score for SIMCA sites was 5.3, the preference subcomponent averaged 5, while conservation suitability was higher at 5.7 (Fig. 4.1). I scaled scores in each component to two anchor points (best and worst case scenarios) - 1.6 and 7.9 for the preference subcomponent; 0 and 9.25 for the conservation subcomponent; and 1 and 8.6 for total suitability. The scaled total suitability scores of Banggi and Lankayan were significantly different, with Banggi having an average score of 3.7 and SIMCA an average of 5.7 ($F(1,27)=4.2$, $p=5.2*10^{-4}$).

### 4.3.1 Sensitivity analysis

The PASI was generally insensitive to the removal of individual attributes, as all deviations fell within 5% of the baseline. The largest deviation of -0.2 occurred when attribute 2 (distance) was removed (Figure 4.2). Systematic removal of increasing numbers of randomly selected attributes from the PASI showed that deviations remained within 10% of the baseline up until 5 attributes were removed (Figure 4.3). Thereafter, deviations increased, and the highest median deviation of 1.9 (out of maximum deviation of 4.9) occurred when 7 attributes were removed. Removal of attributes tended to drive the PASI towards lower suitability scores, such that the median score after removal of 7 attributes from 50 separate iterations was 40% lower relative to the baseline.

PASI results for the 18 Banggi sites were largely insensitive to the removal of individual attributes. The largest deviation of -0.44 (12% change) occurred when the endangered species (ES) attribute was removed (Figure 4.4). Removal of catch, crowding, and ES tended to negatively bias suitability scores, while removal of distance, depth, net revenue (NR), coral cover (CC) and fish abundance (FA) tended to result in positive bias. Deviations in the upper and lower quartiles of estimated suitability scores with removal of catch, distance, depth, and NR were within 5% of the baseline, crowding was 8% of the baseline, and ES, CC, and FA ranged from 2 to 22% of the baseline.

Deviations were more pronounced when only the preference subcomponent (catch, distance, depth, NR, crowding) was considered. In this case, removal of catch, depth, and crowding resulted in negative deviations. The largest median deviation of 7% occurred with the removal of distance. Deviations in the lower and upper quartiles of most estimated preference scores were between 1 and 13% of the baseline, with the exception of crowding which had a lower quartile deviation of 20% from the baseline.

The estimated suitability scores were insensitive to the effects of switching off individual rules, as there was no deviation in all but one case (Figure 4.5). Turning off Rule 21, which relates high occurrence of endangered species to very high suitability outcome, caused a deviation of -0.3 (8% relative to the baseline).

Both the PASI structure and results were relatively insensitive to changes in the threshold level up to a threshold of 0.5. When the threshold level was raised from 0 to 0.5, most deviations stayed well within 10% of the baseline. The absolute magnitude of deviations from the Banggi data set started to increase at a threshold level of 0.6, with the largest deviation of 3.2 (out of maximum deviation of 3.7) occurring at the 0.9 threshold level. In all cases, increasing the threshold level led to negative bias in the estimated suitability scores (Figure 4.6). Deviations from the simulation data set followed a similar trend, but showed less deterioration at higher threshold levels. The largest deviation of 0.5 (out of maximum deviation of 4.4) was reached at the 0.9 threshold level (Figure 4.7).

## 4.4 Discussion

Designating marine protected areas and zoning them for multiple uses is increasingly viewed as a viable approach to protect biodiversity, mitigate user conflict, and manage fisheries. The need is especially prevalent in many developing countries where high biodiversity and fishing dependent communities tend to converge at the same space. A major constraint to using existing spatial planning decision support tools is the large volume of data that is required to develop a useful model, as well as the time and financial commitments required to learn to operate the tool (Loos 2006). I apply the PASI to determine the suitability of 18 marine sites in the proposed Tun Mustapha Park in Banggi, Sabah, for protection.

The PASI's structure is robust, as the elimination of half the attributes in the system did not cause large fluctuations in estimated site suitability scores (Figure 4.3). The PASI was relatively insensitive to variations in the threshold level. At the 0.9 threshold level, the change in estimated suitability score was just slightly over 10% relative to the baseline. In contrast, when results of the Banggi data set were tested for reliability, deviations were up to 90% at the 0.9 threshold level, although they remained relatively low until the 0.6 level was reached. This implies that the PASI will lose its ability to estimate site suitability if I force it to only trigger rules that have a high possibility of being true. Seen another way, the PASI should not be used for binary yes/no problem solving.

The removal of ES caused the strongest negative deviation (median 12% relative to the base line) in estimated total suitability scores. This may be because most sites had high occurrence (median of 7) of endangered species, which resulted in 'very suitable' outcome with high degree of membership. The same test on the data set of 100 simulated sites resulted in a 0 median deviation when ES was removed, with minimum and maximum deviations within 10% of the baseline. The procedure of selecting the maximum of endangered species sighting frequency may have biased ES towards higher values. In the future, ES may have to be rescaled before being input to the PASI.

The attributes with the strongest influence may give us insight to what drives the system. When the preference subcomponent was considered alone, removal of distance caused the largest change (median of 7% relative to base line) while removal of crowding resulted in a 0% median relative to the baseline. This is consistent with my understanding of the high importance fishers place on personal safety, which they strongly associate with distance when selecting fishing locations. In fact, all fishing sites that gained in preference when distance was removed were those that belonged to the 'far' category, that is, located 8 km or more from the closest village. Crowding may be a redundant attribute that can be removed from the PASI as its exclusion had almost no effect on the outcome. In addition, as commented in the rationale section (Ch 3.2.3), I found some ambiguity with crowding that may explain why the net effect of this attribute is negligible.

Catch and net revenue input from Banggi were averages calculated from fishers' daily fishing trips. Using average values may not capture the variance at these sites, which arises from factors such as heterogeneity in fishers' skills (Hilborn 1985) and seasonal fluctuations in fish catches (Teh et al. 2005). This should be kept in mind when interpreting suitability scores from the preference subcomponent. For instance, a site with estimated low preference (i.e., a high suitability score in the preference subcomponent) may still be valued by a fisher who has a particular skill set or in-depth knowledge that can be used to his advantage to catch fish at that site.

Habitat type may influence fishers' spatial decisions, where preference appears to be connected to gear type (Forcada et al. 2011). Interview results supported this behaviour, as I found that hook and line and spear fishers generally preferred coral/reef substrate while some gill netters stated preference for sandy bottoms (L. Teh, unpublished data). At the same time, with one exception, catch logs showed that fishers fished within the same area regardless of the type of gear they used (L. Teh, unpublished data, see Chapter 2). Overlap in gear use across different habitats was similarly observed in artisanal reef fisheries in Kenya (McClanahan and Mangi 2004). In Sulawesi, seagrass meadows were generally preferred by invertebrate collectors, although some invertebrate collectors fished exclusively at coral reef habitat. Seagrass meadows were also popular with other fishers and gleaners, who in addition also fished at reef habitat. (Unsworth et al. 2010). In an effort to minimize complexity, I thus chose to exclude habitat type from the PASI. However, I acknowledge that habitat and gear data may be useful for further stratifying spatial use, and the additional difference they contribute to a preference score can be evaluated in the future.

The significant difference between Banggi and SIMCA scores shows that the PASI is sensitive enough to pick out distinct differences among sites. The lower average suitability score of Banggi sites matches the fact that all 18 of these sites were fishing grounds with varying levels of use; therefore, they were only moderately suitable to be zoned for protection. On the other hand, the higher SIMCA scores coincide with the fact that all SIMCA sites are currently within an enforced MPA.

Overall, SIMCA conservation subcomponent scores were higher than the preference subcomponent. This may be due to the zero catch and net revenue values I assumed for all SIMCA sites, given that the area is closed to fishing. However, the effect of missing data should not greatly diminish the significance of the result, because estimated site suitability scores were insensitive to the removal of either one of those attributes individually, and even when two attributes were removed at once, there was little deviation in estimated scores. Rather, the 'far' distance between SIMCA sites and fishing villages, the closest of which were approximately 20km away, may have accounted for the low preference subcomponent score.

When the preference subcomponent was considered alone, average suitability score for the 18 test sites was only 3.0 (2.2 when scaled), which further highlights that the sites were ‘preferred’ for fishing hence less suitable for being closed to fishing. Two sites that are known to be strongly preferred by fishers had scaled preference suitability scores of 2.4 and 2.8 (keeping in mind that 0 is very high preference and 10 is low preference), which are lower than I expected relative to the average. I speculate this may be because fishers cannot always detect differences in catch or net revenue levels among different fishing grounds (Oostenbrugge et al. 2001, Pet-Soede et al. 2001, Daw 2008a), or fishers may have incomplete knowledge about the conditions at different fishing grounds (Vignaux 1996, Abernethy et al. 2007). Both sites had lower than average catch and net revenue values which may have decreased preference scores for the sites. However, the low catch and net revenue values may not matter to fishers for the reasons noted above.

Furthermore, the values of catch and net revenue in the PASI are only a static representation of attributes that in reality vary seasonally. Alternatively, the lower site preference may be explained if the relationship between catch and net revenue with effort allocation is not linear (Béné and Tewfik 2001, Abernethy et al. 2007, Salas and Charles 2007). In fact, empirical data suggests this may be true of small-scale fishers in Banggi (see Chapter 2), and I accommodated for this to some extent by qualifying catch and net revenue rules under *very far* condition (see Table 3.2). There is also the option of decreasing the weighting of heuristic rules to reflect less certainty in the expressed relationship between levels of catch and net revenue and fishers’ preference.

One of the main assumptions of the PASI is that fishers will not change their preferences. This assumption may be challenged by technological, climate, or economic changes that can increase or decrease fishers’ ability to catch fish. However, empirical evidence points to temporal stability in the use of fishing grounds by artisanal fishers (Begossi 2006, Forcada et al. 2010), and even the introduction of GPS technology did not greatly disrupt fishers’ spatial use patterns in Northern Ireland (McKenna et al. 2008).

The PASI was designed within the context of artisanal reef fisheries in developing countries, which tend to be the data poor regions globally (McClanahan 1999). As such, the suite of attributes and heuristic rules that structure the PASI are most relevant when applied to regions that share the same characteristics. For example, the rules governing distance and fishers' preference may be inconsequential when applied to zoning off shore MPAs where the existing fishing fleet consists of high powered boats equipped with fish finding and processing technology. Nonetheless, regardless of whether they are artisanal fishers in the Mediterranean or boat skippers in the United Kingdom, fishers show a general trend to keep close to their home port (Abernethy et al. 2010, Forcada et al. 2010), albeit some may do so for cost reduction reasons, while others out of concern for safety or detailed knowledge of the region.

The PASI is thus not restricted only to spatial planning in reef ecosystems in developing countries. Membership categories can be easily redefined to calibrate the PASI to local conditions. Similarly, other biodiversity surrogates for ecosystem health can be used in place of coral cover. The value of doing so is that it allows PASI users to gain more insight on the processes that shape the system in question, rather than rely on behind the scenes algorithms that compute a final solution that is then taken at face value.

PASI is practical for data poor and data rich fisheries alike. It estimated site suitability for protection using 8 attributes, in contrast to other reserve planning approaches where anywhere from 20 to upwards of 80 feature types is typical (e.g. Villa et al. 2002, Ban 2008, Grantham and Possingham 2010). In addition to the few attributes, PASI is also capable of handling some loss in data as estimated site suitability results fluctuated only slightly when single attributes were removed in most cases. Fewer data sets have been shown to be as effective as larger data sets in producing similar results to larger data sets (Ban 2008), and a backward looking analysis of reserve creation showed that initial opportunistic placement of reserves based on limited data fared no worse compared to the results systematic planning with much larger data sets would have produced (Hansen et al. 2011). This makes the case for parsimony when it comes to data collection. The important point is that the model understands and captures the various uses and values that define the system being assessed.

I have deliberately not focused on the spatial configuration of the sites that were assessed by the PASI. Habitats, fishing grounds, and even stakeholders' perceptions of the marine spatial environment seldom conform to the uniform geographical grids that are often imposed by conservation planning tools (St. Martin 2001). Studies have shown that the scale at which conservation planning is conducted does make a difference to areas that are identified for inclusion in a conservation network (Erasmus et al. 1999, Shriner et al. 2006). To overcome issues associated with artificial boundaries, I allowed users to define spatial units of any size and at any scale, whether geopolitical, ecological, or biophysical. I feel that this makes the final solution much easier to interpret and implement. For example, PASI output may indicate that grouper spawning ground *x* has a very high site suitability score, or fishing ground *x* is moderately suited for protection. In contrast, other spatial planning software may generate output that is less intuitive, such as planning unit #532 is selected for inclusion in a protected zone. Furthermore, allowing flexibility in spatial scale definition is more practical for data poor regions where information relating to biodiversity, benthic forms, socio-economics, and biophysical features are usually available only in varied scales. In this case, the benefit of having planning units smaller than the spatial resolution of the coarsest data level would not be useful (Shriner et al. 2006).

Planning marine protected areas is an exercise in setting priorities of who wants what to be protected, selecting and measuring attributes that fully represent the system/ marine environment as it relates to the priorities, and balancing priorities so that all groups with an interest are equally treated. The PASI and other conservation planning tools can perform the same task. The advantage of the PASI is its simple rules-based approach provides a quicker, more intuitive alternative to more complex algorithm and data intensive approaches. In data poor conditions, these other tools may hardly be more informative than a manager's informed guess. I envision that the PASI will be useful for regions such as the Coral Triangle, which is not only a hotspot for biodiversity (Allen 2008), but which also sustains the livelihoods of an estimated 120 million people (WWF 2011). Already, systematic planning for multi-use MPAs in the region is underway (Grantham and  Possingham 2010, Varkey 2010). MPA zoning outcomes from existing projects can provide a basis for further validation studies on the PASI, as well as for evaluating the effectiveness of a range of spatial planning tools. As with other conservation planning tools, PASI results are meant to facilitate, and not dictate, the final solution.

**Table 4.1.** Average attribute values (± std. dev.) from 18 Banggi sites and 11 SIMCA sites. Attribute abbreviations NR=net revenue, ES=endangered species occurrence, CC=coral cover, FA=fish abundance.

| | Catch (kg trip$^{-1}$) | Distance (km) | Depth (m) | NR (MYR trip$^{-1}$) | Crowding (no. of boats) | ES (1-10) | CC (%) | FA (no. 100m$^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Banggi | 11±10 | 5±4 | 18±10 | 34±15 | 7±4 | 6±3 | 38±16 | 31±20 |
| SIMCA | 0 | 23±3 | 13±2 | 0 | 1±1 | 7±1 | 56±7 | 41±32 |

**Table 4.2.** Data sources of site attributes in Banggi, Sabah.

| Attribute | Data source |
|---|---|
| Catch | Catch logs, interviews |
| Distance | Google earth map |
| Depth | Interviews, nautical charts |
| Net revenue | Catch logs, interviews |
| Crowding | Catch logs, interviews |
| Endangered species occurrence | Interviews, personal observation, Rajamani and Marsh (2010) |
| Hard coral cover | Harding et al. (2001), Koh et al. (2002), Lee and Chou (2003), Tanzil and Chou (2004) |
| Fish abundance | Harding et al. (2001), Koh et al. (2002), Lee and Chou (2003), Tanzil and Chou (2004) |

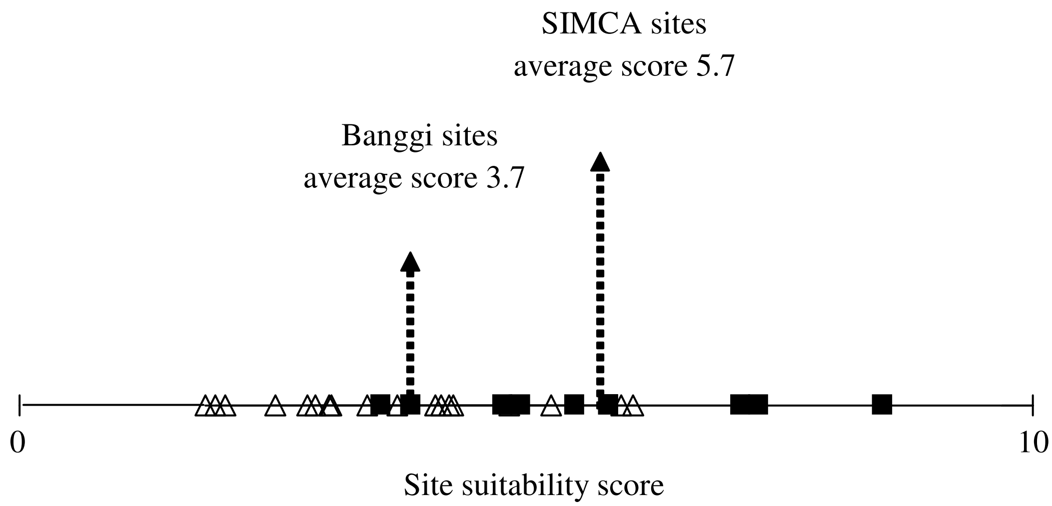


**Figure 4.1.** Estimated scaled total suitability scores for Banggi (Δ) and SIMCA (■) sites are significantly different (ANOVA: see text).

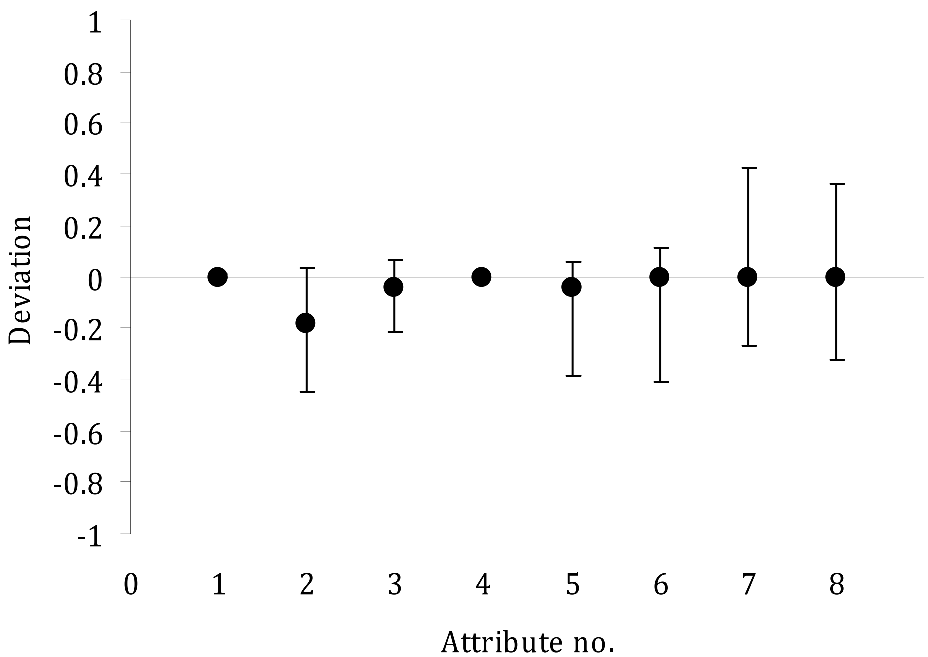


**Figure 4.2.** Deviation in estimated suitability scores of 100 simulated sites when attributes 1 to 8 were removed one at a time then replaced. Bars show the upper and lower quartiles of deviations in estimated site suitability scores. Attribute 1=catch; 2=distance; 3=depth; 4=net revenue; 5=crowding; 6=endangered species; 7=coral cover; 8=fish abundance.

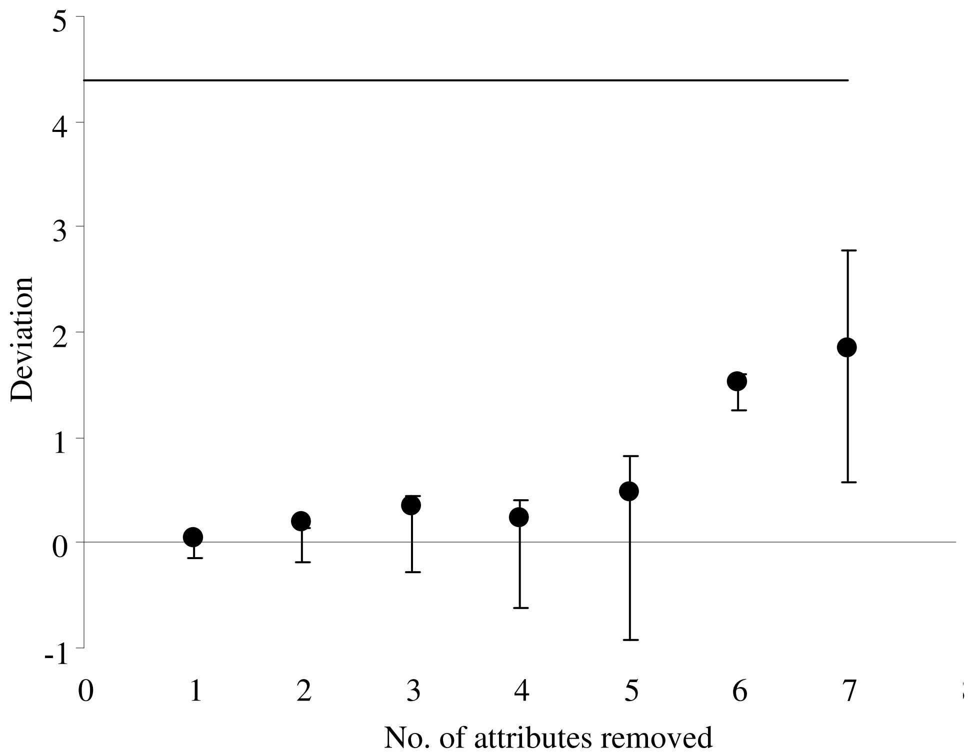


**Figure 4.3.** Absolute magnitude of change in estimated suitability scores when increasing numbers of attributes were randomly removed from the data set. Deviations are the median from 50 random removal sequences. The horizontal line shows the baseline score. The bars show the upper and lower quartile of deviations in estimated suitability scores.

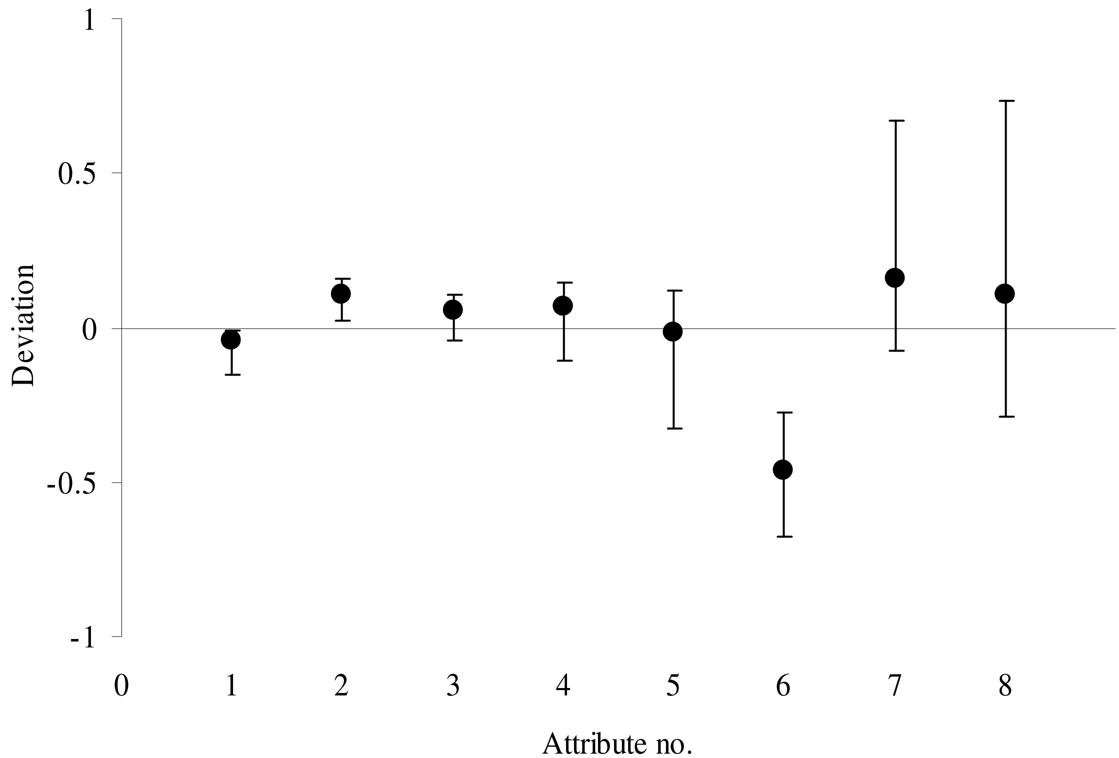


**Figure 4.4.** Deviation in estimated suitability scores of 18 Banggi sites when attributes 1 to 8 were removed one at a time then replaced. Bars show the upper and lower quartiles of deviations in estimated site suitability scores. Attribute 1=catch; 2=distance; 3=depth; 4=net revenue; 5=crowding; 6=endangered species; 7=coral cover; 8=fish abundance.

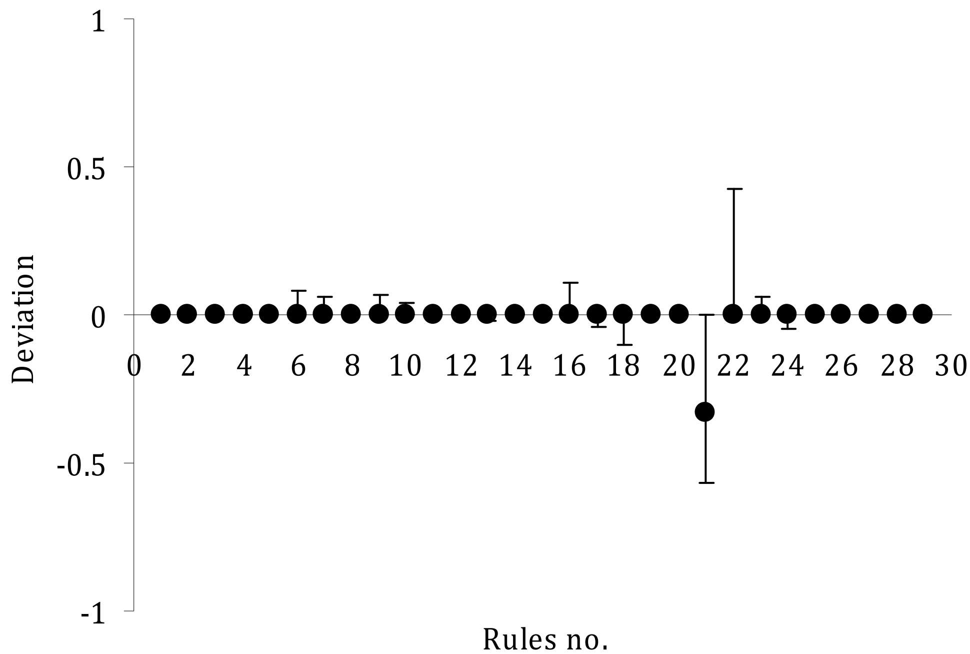


**Figure 4.5.** Deviation in estimated site suitability scores of 18 Banggi sites when individual rules (numbers 1 to 28) were switched off one at a time. Bars show the upper and lower quartiles of deviations in estimated site suitability scores.

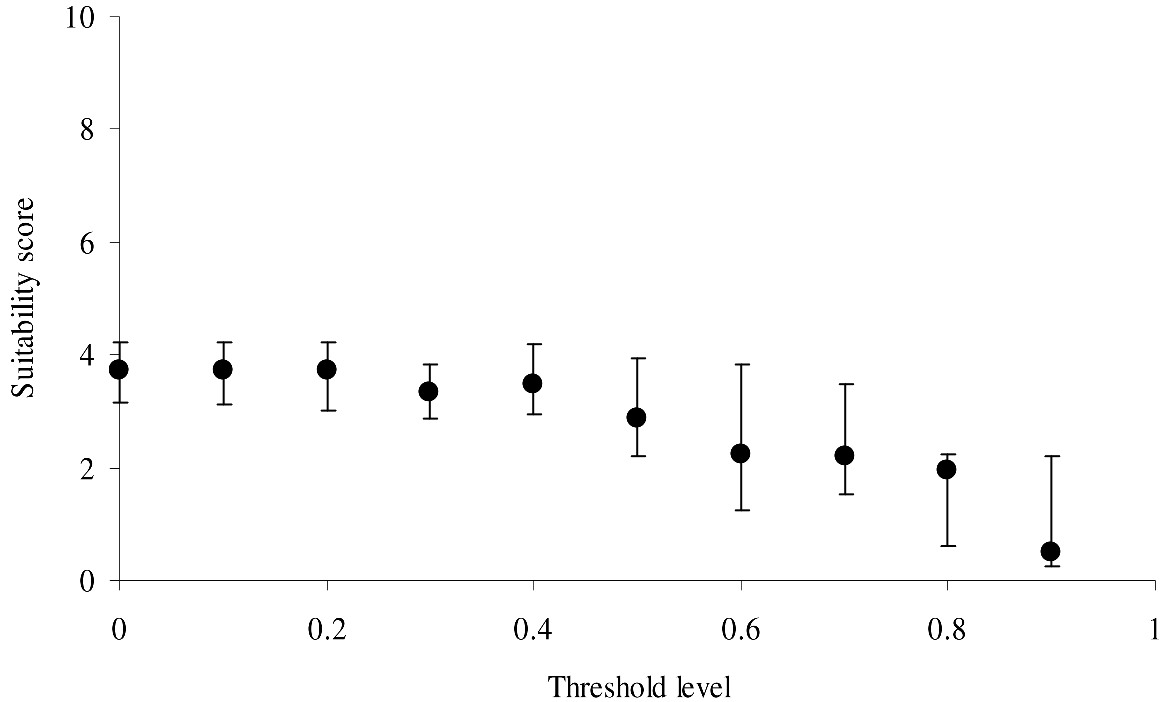


**Figure 4.6.** Median estimated suitability scores of 18 Banggi sites when threshold level was incrementally increased from 0 to 0.9. Bars show the range of minimum and maximum estimated suitability scores.

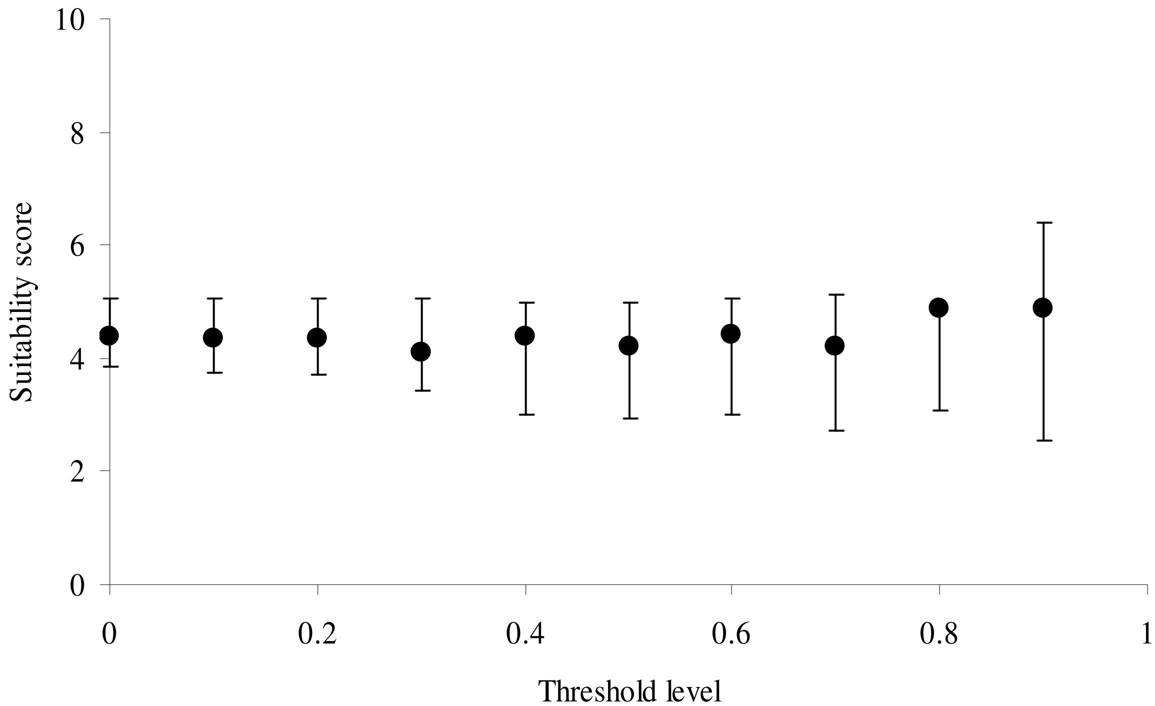


**Figure 4.7.** Median estimated suitability scores of 100 simulated sites when threshold level was incrementally increased from 0 to 0.9. Bars show the range of minimum and maximum estimated suitability scores.

# Chapter 5: Comparison of marine protected area site selection outcomes from a community approach and a fuzzy logic approach

## 5.1 Introduction

Marine protected areas are used for multiple purposes - they can help to mitigate human threats to the coastal ecosystem (Halpern et al. 2008), address biodiversity loss (Sala and Knowlton 2006), restore fisheries and ecosystem processes (Sumaila et al. 2000, Russ and Alcala 2004, McClanahan et al. 2007, Goñi et al. 2008), and generate socio-economic benefits (Unsworth et al. 2010, Mwaipopo 2008, Govan 2009). The use of MPAs is rising globally (Wood et al. 2008), and in recent years, MPAs have featured prominently in marine conservation agendas for biodiversity rich areas in the developing world. For example, the Coral Triangle is a multi-national effort to establish networks of MPAs in Southeast Asia and western Oceania (CTI 2009).

High human reliance on marine resources in developing countries is a challenge for implementing MPAs, which specifically seek to limit or restrict fishing in selected areas. Indeed, theories on the ecological effects of marine protected areas are based on the condition that no fishing takes place within MPA borders (Ballantine 1997, Ward et al. 2000). Carrying on with conservation without addressing socio-economic complexities is liable to be met with limited success (Mascia 2003, Cinner 2007). Community support for MPA regulations is thus seen as a key factor in achieving successful biological and socio-economic outcomes (Crawford 2009).

Community participation in MPA planning has generally been associated with better attitudes towards the MPA (Crawford 2009, Versleijen and Hoorweg 2009) and hence higher compliance. Zoning plans that do not meet consensus are ineffective; for example, conflicts over access to resources may arise (Lewis 1996), or fishers may ignore zoning regulations (Mora et al. 2006, Crawford 2009). Opinions and preferences of communities are thus an important consideration when prioritising sites for protection. However, incorporating community preferences to MPA spatial planning is viewed as an ad hoc process by some researchers, who tend to favour a systematic approach to planning MPAs. Typically, this involves designing MPAs to achieve specific targets in representing biodiversity, species, and habitats (Margules et al. 2002, Leslie 2005). This process is frequently facilitated by software that are supported by academic institutions or environmental non-governmental organizations (NGOs).

Community driven and representation driven approaches to MPA design each have their drawbacks. Even where MPAs have been formed with community participation, internal conflicts within the community can erode the system (Russ and Alcala 1999). In addition, community driven site selection outcomes may not capture the full range of biodiversity and ecological features that are necessary to sustain the marine ecosystem. On the other hand, systematic planning for representation relies heavily on data availability, the lack of which may delay the entire process (Grantham et al. 2009). In developing countries, this is probably the biggest challenge, notwithstanding the fact that socio-economic data are even rarer to come across than biological data; hence, systematic planning for representation may overlook social aspects that are relevant to communities.

A practical approach to prioritising and selecting sites for marine protected area would thus be one that incorporates communities' spatial preferences within a systematic planning framework. In Chapters 3 and 4, I demonstrated that the PASI fulfills such a role. In this chapter, I investigate the extent to which PASI site suitability scores match the protected area selection from a community driven process. I make this comparison because one of the unique aspects of the PASI is its capability to reflect fishers' spatial preferences. Overlap in sites identified by both methods will validate PASI's ability to reflect community preferences. I use a case study of the Maliangin Sanctuary in Banggi, Sabah, Malaysia, as the basis for the comparison.

Banggi is in the process of being gazetted as part of the Tun Mustapha Park (TMP), a multiple use MPA. When formalized, the TMP will cover an area of approximately 1 million hectares. Roughly 80,000 people live within the proposed TMP, most of whom make a full or partial living from the sea (Jumin and Kassem, undated). Many fishers in the affected area have limited flexibility to adapt to changes in access to their existing fishing grounds (Chapter 2); therefore, I focus on prioritising areas that impose minimal loss in fishers' access to their fishing grounds.

In 2006, efforts were initiated to begin prioritising sites for protection, i.e., closed to fishing. Maliangin Besar island (hereafter referred to as Maliangin) was chosen as the first pilot site. The process of creating the new Maliangin Sanctuary was led by WWF-Malaysia, a local branch of a global environmental NGO, in partnership with the state departments Sabah Parks and Sabah Department of Fisheries. Local communities were also involved in process, and the Maliangin Island Community Association (MICA) was created to represent local interests and facilitate the creation of Maliangin Sanctuary. The purpose of Maliangin Sanctuary was to demonstrate the benefits of a co-managed marine protected area to the local fishing communities of Banggi and the larger region. Specific objectives included demonstrating possible spill-over effect, improving biodiversity, and generating socio-economic benefits to the local community.

## 5.2 Methods

### 5.2.1 Study site

Maliangin is less than 2km$^2$ in area, and is located about 5km southwest of the main island of Banggi. In 2006, there were about 12 fishers on Maliangin, who fished daily in the waters surrounding the island. In addition, fishers from neighbouring villages on Banggi, and occasionally fishers from outside Banggi, also fished near Maliangin. The waters surrounding Maliangin were not subject to any access restrictions, and Maliangin fishers expressed no inclination to prohibit fishers from other villages from fishing close to their village. However, Maliangin fishers did complain occasionally about commercial trawlers and purse seiners that fished too close inshore near their village (Teh et al. 2007).

Maliangin fishers fish primarily with hook and line, followed by traps and spears. They conduct single-day trips using wooden plank boats powered by inboard engines that are typically 7 horsepower in size. Fish catches are composed of demersal reef fishes and reef associated pelagics (Teh et al. 2007). Maliangin fishers are specially interested in trolling for Spanish mackeral and catching live coral grouper. During certain times of the year, fishers and/or members of their household glean for sea cucumbers and other invertebrates at Maliangin Kecil island.

All Maliangin fishers fish within an area referred to as Maliangin fishing ground (MFG), which covers an area of roughly 22 km$^2$. Maliangin fishing ground covers zone B and part of zone C as described in Table 2.2 (Figure 5.1). On average, Maliangin fishers made about 95% of their fishing trips within 4 km from Maliangin island (Chapter 2). In general, fishers fish over patch and fringing reefs in the MFG that are 8 to 40m deep, while gill netters occasionally fish over muddy substrate. Maliangin fishers started fishing full-time in the 1980’s after the decline of the copra industry, which had been the main economic activity for island residents. Prior to that, fishing was done at a subsistence level. The MFG has thus been used continuously by fishers from Maliangin for at least the past 30 years.

### 5.2.2 Community consultation

The process for designing Maliangin Sanctuary began in 2006 when WWF initialized consultations with representatives from Maliangin and three neighbouring communities to identify potential sites for protection. Prior to this, fishers’ spatial use patterns were not well understood. Existing criterion for site prioritisation was WWF’s aim to achieve a 30% coral reef representation in the sanctuary (R. Jumin, pers. comm.). Two rounds of consultations led to the first proposal drawn by WWF outlining the boundary of Maliangin Sanctuary (Figure 5.2). In this first proposal, zone 1 incorporated two areas identified by the communities as suitable sites for protection, while zones 2 and 3 were selected for protection to meet WWF’s coral reef target. The first proposal was rejected by the communities because of the inclusion of an important fishing ground, S7, in zone 3 where no fishing was allowed. In addition, Maliangin fishers were worried about their ability to access Maliangin Kecil island which was covered within zone 3 (R. Jumin, pers. comm.). Further rounds of negotiations with MICA ensued over the sanctuary boundary. In 2009, a compromise was reached wherein the boundary of zone 3 was altered to exclude S7, yet still retain enough coral reefs to meet WWF’s target (Figure 5.2). This version of Maliangin Sanctuary was accepted by MICA, and knowledge of its existence is slowly spreading to other communities in Banggi. I use this version of Maliangin Sanctuary as the basis of our comparative analysis.

### 5.2.3 Fuzzy logic approach

I used the spatial management tool PASI to identify sites within the study area that are suitable for being protected, i.e., closed to fishing. The PASI is a fuzzy logic expert system that facilitates protected area site selection by identifying sites that minimize socio-economic impact on fishers, yet satisfy conservation criteria (Teh and Teh 2011). Impact on fishers is minimized by avoiding selection of fishers' preferred fishing grounds, whereby preference is determined by the spatial attributes catch (kg trip$^{-1}$), distance (km), depth (m), revenue (MYR trip$^{-1}$), and crowding (number of boats in vicinity). Coral cover (% hard coral cover), fish abundance (no. of fish 100m$^{-2}$), presence of seagrass (yes/no) and endangered species occurrence (scale of 1-10) were used as biodiversity surrogates. Input variables to the PASI are assigned to fuzzy membership categories with an associated degree of possibility. Fuzzified inputs then trigger specific heuristic rules that relate a given condition (e.g., If catch is high) with an outcome of site suitability (e.g., Then suitability is low). A suitability score is computed for each of the preference and conservation value subcomponents; both subcomponents are weighed according to a user defined proportion and summed to a final suitability score. Upper and lower bounds are calculated around each final score. Finally, I scaled all suitability scores to two anchor points, which were the best and worst case scenario outcomes.

I allocated a 50/50 percent split in the contribution of the preference and conservation subcomponents to total suitability. Rules were weighted to reflect the relative importance of attributes in fishers' spatial decision making, based on fishers' responses during interviews (Chapter 2). There was also a subjective element in the weightings that reflected the degree of confidence I had in the outcomes expressed by the rules. Rule weightings varied from 0 to 1, where 1 means high importance or high confidence, and were assigned as follows: Crowding (all suitability outcomes) = 0.25; depth (very deep) = 0.25; catch and revenue (all suitability outcomes) = 0.5, endangered species (all suitability outcomes) = 0.5; distance (very near, very far) = 0.75; depth (shallow, little deep, deep) = 0.75; coral cover and fish abundance (all suitability outcomes) = 0.75; distance (near, far) =1.

I considered two scenarios to account for limited biodiversity data. Scenario 1 'megafauna' included only the attribute endangered species in the conservation subcomponent. Scenario 2 'reef health' included the attributes endangered species, coral cover, and fish abundance. Both scenarios included all attributes in the fisher preference subcomponent.

### 5.2.4 Method for comparing community based with fuzzy logic approach

I assessed the overlap in sites selected for protection from the community approach and the fuzzy logic approach. To do this, I used the community map as the basis for comparison, then calculated the number of convergently classified sites divided by the total number of sites (Ban 2008). Sites that were selected for protection from the community approach are those within the no fish zones on Figure 5.2. For the fuzzy logic approach, I considered sites with scores of more than 6 to be adequate for protection. Six was defined as the minimum cut off score for protection as it was the average value of the upper quartile of the set of suitability scores from scenario 1, scenario 2, and the preference subcomponent.

I calculated Cohen's kappa statistic in SPSS to test for inter-rater agreement between the two approaches. The kappa statistic is a chance-corrected measure of agreement that examines the degree to which two raters concur in their assignment of N items into x categories. In this case, the community and fuzzy logic approaches are the two raters, which assign 12 sites into 2 categories of protection - protected and not protected.

I then conducted a multidimensional scaling (MDS) analysis using PRIMER 5 software to examine if attributes used in the PASI to characterise sites delineate fishers' site preferences. MDS is a multivariate statistic technique used for qualitatively exploring similarities in a set of data. Input variables to the MDS were catch, distance, depth, revenue, and crowding. Similarity was measured as the Euclidean distance between pairs of samples, in this case, the similarity between sites. MDS ordination maps the position of each site such that those that are similar are positioned close together, while those that are less similar are positioned further apart. Sites were factored by 2 factors, 'actual' fisher preference and suitability scores from the PASI preference subcomponent. Actual fisher preference was measured by trip frequency (number of visits) data from catch logs and personal observations of site usage, whereby higher trip frequency and site usage was assumed to indicate higher preference. Three levels of fisher preference and site suitability were defined- low, moderate, and high. I visually examined whether there was any clustering of sites by preference and suitability level, and used the analysis of similarity (ANOSIM) function in PRIMER 5 to test for differences in sites grouped by preference and suitability level. By doing so, I could infer the extent to which attributes used in the PASI to measure fishers' site preference actually did so.

## 5.3 Results

Figure 5.2 shows the boundaries of 3 no take zones within the Maliangin Sanctuary that were agreed upon after a community consultation process that lasted 3 years. The main difference between the final and initial proposals is zone 3's boundary, which was redrawn to specifically exclude site S7. Final designated no take zones covered approximately 9km$^2$, taking up about 40% of MFG.

There was a 75% overlap in between sites chosen for protection through the community process and the PASI in scenario 1 (megafauna), while scenario 2 (reef health) had a 58% overlap. However, calculation of Cohen's Kappa showed there was no significant agreement between the two approaches in scenarios 1 and 2, i.e. the overlap in assigning sites to protection was not greater than that which would have happened by chance.

The PASI calculated total site suitability scores for 12 sites in MFG (Table 5.1). Site suitability scores were scaled to the best and worst case scenarios of 7.6 and 1, respectively. In scenario 1, S1 had the highest score (i.e., very suitable for protection), while S11 had the lowest score. Five of the assessed sites were suitable for protection, which I defined as sites having scores greater than 6. Out of these 5 sites, 3 fell within the no take zones determined by the community consultation. Of the 7 sites scored as being not suitable for protection by the PASI, 1 was protected in a no take zone determined by the community approach. When site suitability scores were scaled in scenario 2, S10 was scored as the most suitable site while S11 was assessed as being the least suitable for protection. In scenario 2, only 3 sites were assessed by the PASI as being suitable for protection, of which only 1 agreed with the decision of the community approach. Out of 9 sites deemed not suitable for protection by the PASI, 3 were selected for protection by the community approach.

Multidimensional scaling showed clustering in sites that were highly preferred by fishers (Figure 5.3). Similarly, there was clustering to one side of the MDS plot by sites with low suitability when factored by the preference subcomponent score (Figure 5.4). ANOSIM tests indicated a significant difference between sites factored by 'actual' fisher preference ($p<0.01$, $R=0.457$) (Table 5.2), and a significant difference between sites factored by preference subcomponent score ($p<0.01$, $R=0.906$) (Table 5.3). In both cases, sites categorized as low appeared to be most dissimilar from the high and moderate sites (Table 5.1 and 5.2). The R values suggest a strong difference among sites factored by preference subcomponent scores, and a moderate difference when sites were factored by fisher preference.

## 5.4 Discussion

Community support is a crucial element for successful MPA implementation, and there is growing recognition that human preferences have to be integrated directly into the MPA site prioritisation process (Ferse et al. 2010). How to incorporate community preferences and opinions in a systematic planning framework is a topic that has not been fully explored. I addressed this gap by applying the PASI to score the protection suitability of sites in Maliangin fishing ground, with the aim of examining how well the PASI matches the local communities' selection of sites for protection.

Suitability scores from the preference subcomponent alone appeared to be reflective of fishers' fishing location preferences. High suitability scores from the preference subcomponent should be interpreted to mean that fishers have low preference for that site, hence the site is highly suitable for protection. The community selected two sites contained within zone 1 as their choice for a no fishing area. S8 fell within zone 1 and was similarly scored as being highly suitable for protection, based on total suitability (6.2) as well as on preference alone (8.1). Fishers' concern about gaining access to Maliangin Kecil island was correspondingly reflected in the low suitability score for S3. Their very high preference for S7 was confirmed by the site's scaled score of 0, meaning that the PASI rated it even less suitable for protection than the worst case scenario. Sites S5 and S9 also achieved low scores, which is not unexpected as along with S7, these three sites have the reputation of being fishing grounds with "lots of fish" among local fishers (unpublished interview data, 2007, 2009).

Total suitability scores reflect that compromises were made in balancing conservation and fishers' interests. Despite fishers' high preference for S3, the site was included within a no fishing zone because of extensive coral cover in the area, as well as the importance of Maliangin Kecil island as a turtle nesting ground. This was reflected in S3's relatively high total suitability scores, ranging from 4.5 to 7.4 in scenarios 2 and 1, respectively. When the conservation value of S7 was considered, its total suitability score rose to 3.9 in both scenarios, indicating that it was moderately suitable for protection.

The PASI indicated that there were three suitable sites for protection that were not selected for protection during community consultations. These sites, S1, S2, and S10, are used infrequently by fishers, based on the number of trips taken to S1 and S2 from catch log records, as well as personal observations of fishing activity at S10. S10 may be an appropriate candidate site for protection as its proximity to shore facilitates compliance and enforcement efforts (Crawford 2009, Jupiter and Egli 2011), and it contains some seagrass habitat (Rajamani 2009) for endangered species such as dugongs, which have been sighted and/or caught within the vicinity (The Star Online 2009). However, designating S10 as a no fishing zone blocks fishers' access to Maliangin Kecil island, making S10 less appropriate for closure. Although infrequently used, S1 may be more suitable for seasonal closure as the vicinity of the site becomes important during the annual southwest monsoon when it offers fishers a relatively safe and sheltered place to fish.

I omitted coral cover and fish abundance data from scenario 1 because the data were only available for 4 sites. As well, the data were sourced from underwater surveys conducted in the early 2000s, and as such may not be representative of current coral reef health conditions. The addition of coral cover and fish abundance data decreased the total suitability scores of 3 out of 4 sites with data, resulting in scores that were on average 30% lower. Only 3 sites were identified as being suitable for protection, compared to 5 sites in scenario 1. The results indicate that poor to moderate coral reef health in MFG negatively influenced overall site suitability scores. Faced with this situation, and with the knowledge that reef health may have changed substantially in the course of 10 years (Gittings et al. 1993, Stobart et al. 2005) managers can err on the conservative side and opt to protect the larger number of sites identified in scenario 1.

The ambiguity in results that arose from the inclusion of coral health data raises the issue of over-relying on data and accepting results at face value. MPA zoning exercises that make use of 50, 100 and possibly more layers of data covering multiple biodiversity and biophysical features are not unusual. Yet, with so many different layers it may be difficult to detect if results are being unduly biased by a single feature, and the influence of poor quality data can be masked. I demonstrated that even without two attributes the PASI still estimated site suitability scores that were reasonable. Furthermore, using less rather than more data makes the model more transparent and the results easier to interpret. On the other hand, I acknowledge that PASI outcomes may not capture areas that maximize biodiversity representation in the area, and this can be considered a shortcoming in places where marine census data are available. In data poor regions such as Banggi, biodiversity attributes can be added to the conservation subcomponent as knowledge becomes available; I added seagrass attribute to the conservation subcomponent in this chapter. In addition, the conservation subcomponent can be allocated more weight if biodiversity is the overriding objective.

The spatial resolution of data used in the PASI is coarse, and results should not be used to identify areas at a resolution finer than that which fishers typically associate with a particular site name. Thus, sites identified in this paper should not be used to pin point specific locations. Although the spatial representation of PASI outcomes is patchy, I avoid imposing artificial values on areas where no knowledge exists. Areas of identified high or low suitability can be connected and configured into zones using visual judgement and on-the- ground knowledge of local conditions. PASI results in this study are biased towards lower scores because all the assessed sites are used for fishing, therefore have a human preference value. If non fished sites are included in the assessment, overall suitability scores also increase accordingly.

The PASI captured fishers' preference for fishing locations, which was most apparent when suitability scores from the preference subcomponent were analysed apart from total suitability score. The MDS showed that a certain combination of catch, distance, depth, net revenue, and crowding distinguished highly preferred sites from other sites. The similarity in patterns observed in Figures 5.3 and 5.4 suggests that i) site suitability scores from the PASI's preference subcomponent infer fishers' actual preferences, as measured by how frequently they visit a site; and ii) the suite of attributes in the preference subcomponent captures underlying factors that influence fishers' site preferences.

A fuzzy expert system such as the PASI can be especially practical for data poor regions that seek to create protected zones where there is high reliance on marine resources. Without extensive prior knowledge about fishers' spatial use preferences, managers can still estimate sites of high and low importance to fishers from PASI output. This approach may decrease the time, personnel, and financial resources that have to be dedicated towards community consultations. For example, the designation of no take zones in Maliangin Sanctuary might have been quicker if S7 had not been included in the initial proposal. More generally, making informed proposals that account for fishers' preferences at the very beginning of the site prioritisation process can promote good relations between involved groups, and help in developing communities' trust in, and commitment to the marine protected area creation process (Sesabo et al. 2006, Ferse et al. 2010).

**Table 5.1.** Scaled suitability scores estimated for Maliangin sites. Scenario 1 includes preference attributes and endangered species only. Scenario 2 includes preference attributes, endangered species, coral cover, fish abundance, and seagrass presence for S1-S4. Preference refers to suitability scores based on the fisher preference subcomponent only. Bolded scores indicate that the site is considered suitable for protection.

| Site | Scenario 1 | Scenario 2 | Preference |
|---|---|---|---|
| S1 | **8.9** | 5.6 | **6.2** |
| S2 | 5.9 | **6.0** | **7.3** |
| S3 | **7.4** | 4.5 | 0.9 |
| S4 | **7.6** | 4.8 | 1.5 |
| S5 | 4.0 | 4.0 | 0.5 |
| S6 | 4.2 | 4.2 | 1.0 |
| S7 | 3.9 | 3.9 | 0 |
| S8 | **6.2** | **6.2** | **8.1** |
| S9 | 4.3 | 4.3 | 1.5 |
| S10 | **8.3** | **8.3** | 4.0 |
| S11 | 1.1 | 1.1 | 4.1 |
| S12 | 4.2 | 4.2 | 1.0 |

**Table 5.2.** Results of one-way ANOSIM test comparing similarity in sites by fishers' preference levels. Significant results are bolded, where significance was set at p=0.05.

| | R value | p value |
|---|---|---|
| Global test | **0.457** | **0.006** |
| Pairwise tests | | |
| Low, high | **0.738** | **0.008** |
| Low, moderate | 0.291 | 0.095 |
| High, moderate | -0.109 | 0.571 |

**Table 5.3.** Results of one-way ANOSIM test comparing similarity in sites by their estimated suitability scores in the preference subcomponent. Significant results are bolded, where significance was set at p=0.05.

| | R value | p value |
|---|---|---|
| Global test | **0.906** | **0.001** |
| Pairwise tests | | |
| High, low | **0.857** | **0.008** |
| High, moderate | 0.667 | 0.2 |
| Low, moderate | **1.0** | **0.028** |

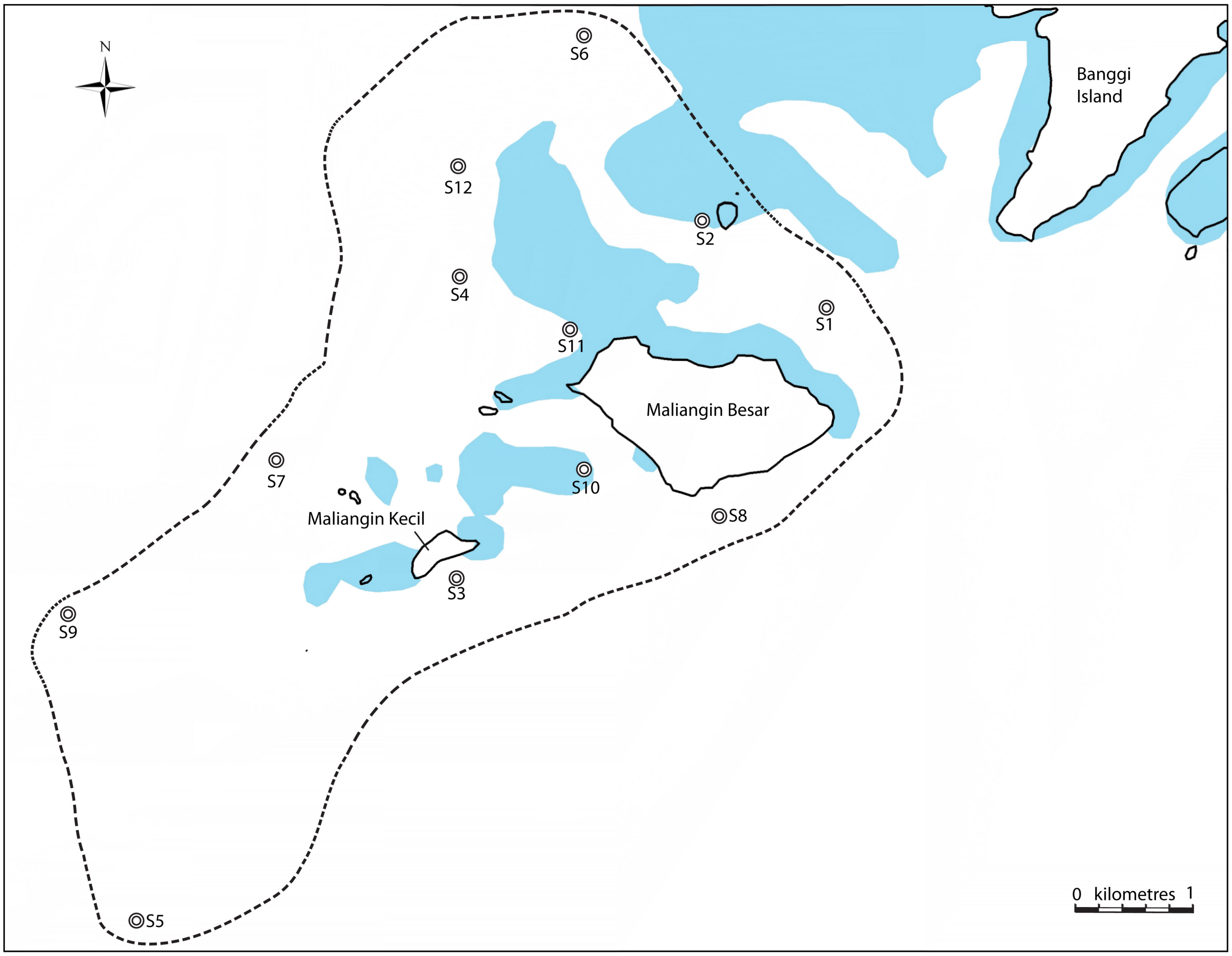


**Figure 5.1.** Maliangin fishing ground is outlined by the dotted line, and the locations of assessment sites are marked by circles. Shaded areas indicate coral reefs. The map is not drawn to scale, and the fishing ground boundary and all site locations are approximate.

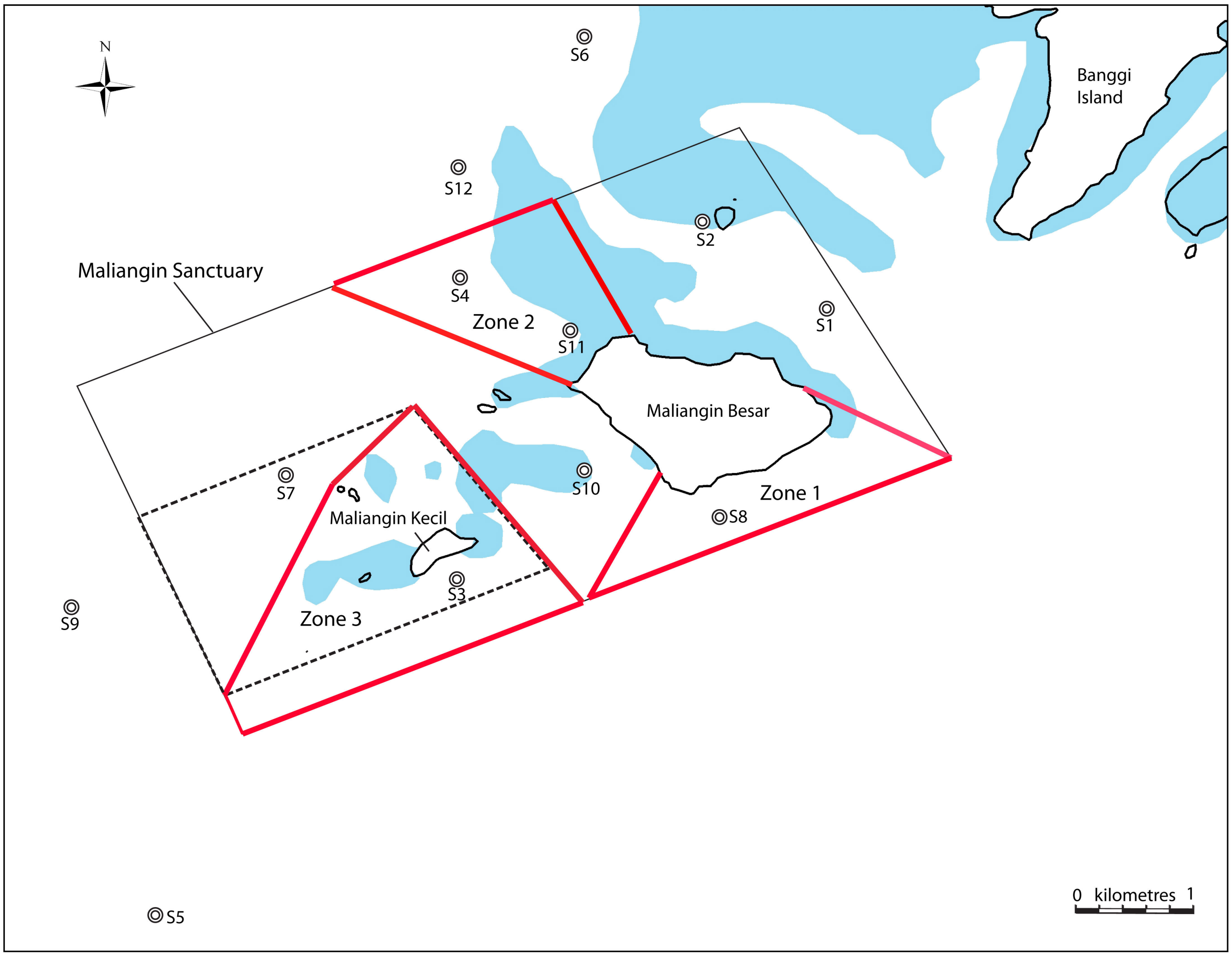


**Figure 5.2.** The final configuration of no take zones (zones 1 to 3) within the Maliangin Sanctuary, where bolded lines are boundaries of no take zones. The dotted line shows the original proposed boundary of zone 3, which was subsequently altered to exclude S7. Shaded areas indicate coral reefs. This map is reproduced from an original created by WWF-Malaysia. This map is not drawn to scale, thus Sanctuary boundaries may not be exactly as shown on the original.

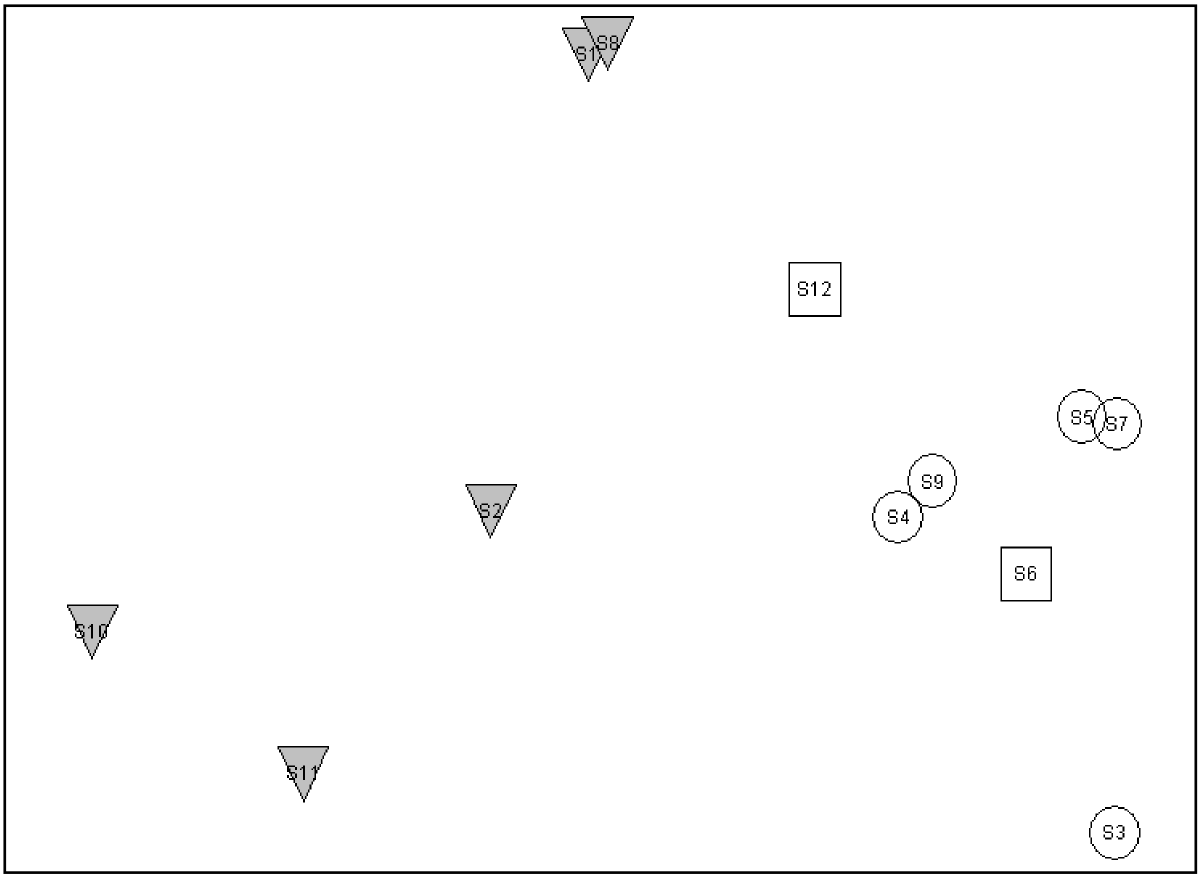


**Figure 5.3.** MDS ordination of sites by the variables catch, distance, depth, net revenue, and crowding. Sites are factored by trip frequency as recorded on catch logs and personal observations of site usage. Levels of trip frequency are ○low; □moderate; ▽high.

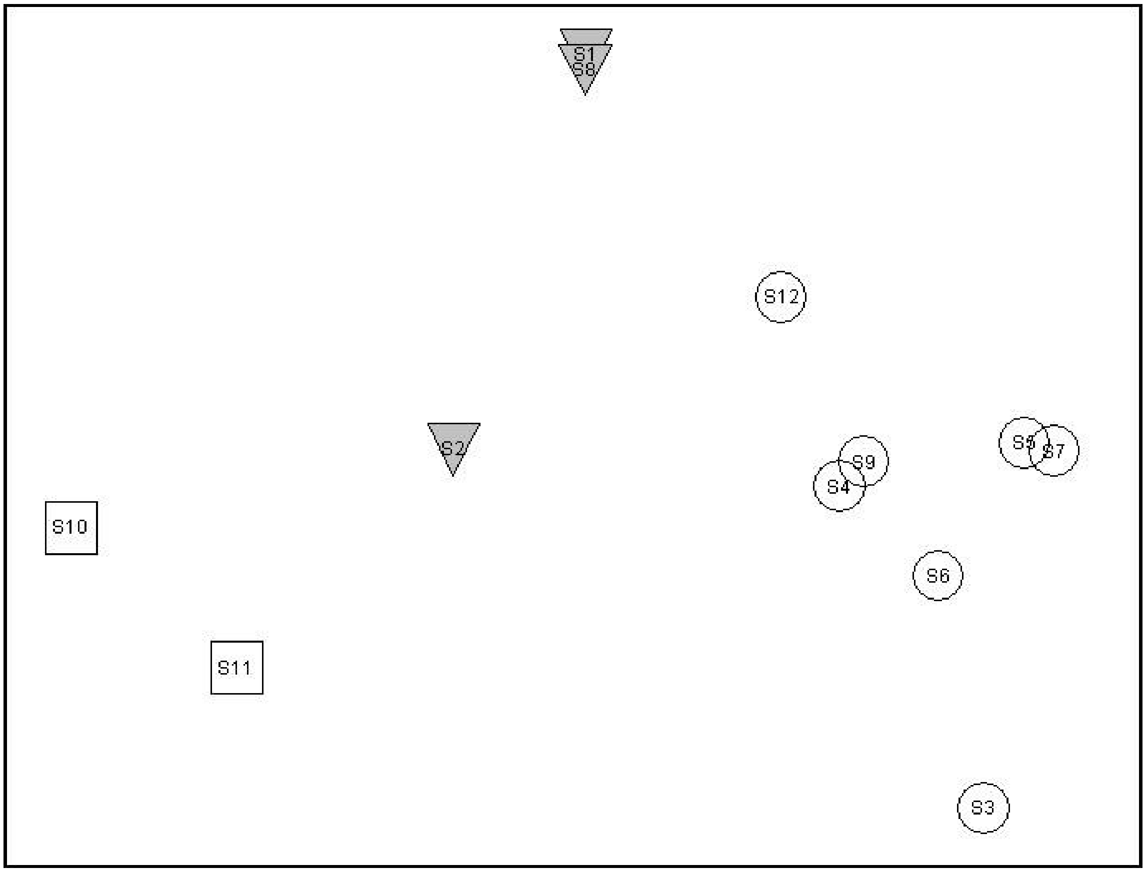


**Figure 5.4.** MDS ordination of sites by the variables catch, distance, depth, net revenue, and crowding. Sites are factored by suitability scores from the PASI's preference subcomponent. Levels of suitability are ○low; □moderate; ▽high.

# Chapter 6: Conclusion

This thesis is centred on the development and application of a decision support tool for zoning marine areas. I started the thesis by addressing my first research question 'What factors influence fishers' spatial use patterns?'. I answered this by conducting an empirical investigation of fishers' spatial behaviour and examining fishers' perceptions of the marine environment in Chapter 2. Insights from Chapter 2 formed the knowledge base of a fuzzy logic expert system, the protected area suitability index (PASI), for assessing the suitability of sites for protection from fishing. I outlined the rationale and framework of the PASI in Chapter 3, then in Chapter 4 I conducted a sensitivity analysis to test the reliability of the PASI's structure and results. Lastly, I validated the PASI results in Chapter 5 by comparing PASI output with the outcome of a community driven marine sanctuary zoning process in Banggi, Sabah.

I will next summarise my main research findings and discuss the significance of my results in the context of small-scale fisheries and marine spatial management. I will identify assumptions and limitations of the research, then conclude with suggestions for applying the research and for future courses of study.

## 6.1 Main findings

### 6.1.1 What factors influence small-scale fishers' spatial use patterns?

Fishers are generally assumed to act like rational decision-makers who will allocate their fishing effort in such a way as to maximize net benefits (eg., revenue). My main findings are: i) fishers fish within preferred resource spaces that are in most cases not where net revenue is maximized; and ii) fishers tend to fish where net revenue to distance ratio is maximized. Furthermore, the majority of fishers choose not to change their spatial range even under favourable scenarios such as having cheaper petrol. Other authors have similarly found fishers' effort allocation to deviate from what conventional economic or ecological behavioural models would predict (Béné & Tewfik 2001, Salas & Gaertner 2004, Abernethy et al. 2007), and there is increasing interest in how social and other human dimension factors affect spatial decisions (Charles & Wilson 2009, Fulton et al. 2011). My findings suggest that fishers' spatial use patterns can be explained in the context of their perceptions and mental maps. While others have explained fishers' travel distance in terms of cost trade-offs (Daw 2008a, Lopes & Begossi 2011), I show that fishers tend to fish close to home because of the association of 'close' with 'safe' fishing conditions. My findings highlight the need to recognise the role that perceptions play in influencing fishing decisions (St. Martin 2001, Charles & Wilson 2009).

My findings also suggest that fishers tend to be risk averse, as they were willing to trade off higher revenue for the assurance of safety. This result is consistent with the findings of some authors (Bockstael and Opaluch 1983, Mistian and Strand 2000, Smith and Wilen 2005), although more recent studies appear to support the finding that fishers are risk neutral or risk takers (Eggert & Lokina 2007, Nguyen & Leung 2009). Differences in experimental approach, analytical framework, and the type of fishery being studied (artisanal/ commercial) could have accounted for the varied outcomes. Nonetheless, my findings have implications for fisheries policies which, along with international development aid programmes, are designed based on basic assumptions of fishers' risk preferences.

### 6.1.2 How can human perceptions be integrated in marine spatial planning?

Fuzzy logic provides the means by which human perceptions can be integrated into a spatial management tool. In Chapter 3, I explained the procedure for doing so. First, I showed that the way fishers 'see' the world can be quantified using linguistic categories arranged in fuzzy sets, which are defined by fuzzy membership functions. Second, I demonstrated the way heuristic rules can be used to describe non-linear relationships that mimic how systems in the real world behave. For instance, I used rules to qualify fishers' spatial preferences based on empirical evidence from Chapter 2.

I then showed that the PASI framework and results are reliable, as estimated site suitability scores are not excessively affected by individual rules or the elimination of information. Interestingly, the distance attribute caused the largest deviation in site suitability scores, which implies that it is the strongest driver of the system. This outcome reinforces the finding in Chapter 2 that distance is a leverage point for fishers' spatial decisions. PASI results are able to distinguish between areas that are actively fished and those that are protected based on differences in 8 attributes related to fisheries, biophysical, and biodiversity properties (Chapter 4).

### 6.1.3 Is a fuzzy logic based spatial planning approach viable for zoning marine protected areas?

I showed that the PASI can estimate fishers' preference for fishing at a site. I did this by measuring the overlap in sites that were chosen for protection by a community consultation process and by running the PASI. There was a 75% overlap when suitability was scored using only the suite of fisher preference attributes and the attribute 'endangered species'; however, the level of inter-rater agreement was not statistically significant. The PASI's fisher preference subcomponent was capable of picking out sites that are important fishing grounds for local fishers. One site that the PASI rated as being not suitable for protection was included in the no take area decided by the community process, likely to satisfy coral reef representation targets. Protection suitability estimates generated by the PASI were reasonable when considered in the context of local conditions, thus the fuzzy logic expert model can be a viable alternative for zoning MPAs in data poor regions. More broadly, the analysis in this chapter highlights that MPA site selection is a challenge of balancing multiple needs, and results generated by software should best be interpreted with a firm understanding of human and environmental interactions on the ground.

## 6.2 Significance of results

This research is, to my knowledge, the first to apply empirical knowledge of fishers' behaviour to the development of a decision support tool for zoning marine areas. Inability to anticipate how fishers will reallocate their fishing effort can lead to poor biological outcomes in MPAs (Gambino et al. 2003, Forcada et al. 2010). I address this shortcoming by designing the PASI to anticipate sites that fishers will prefer to fish at, then scoring preferred sites as being not suitable or having low suitability for protection. In contrast, conservation planning tools used for marine zoning tend to deliver optimal solutions of spatial configurations that achieve target levels of ecological and biological features (Crossman et al. 2005). However, fishers and other stakeholders are not explicitly represented by these tools.

The ability to anticipate where fishers will prefer to fish is derived from insights on factors that are important to fishers in their daily spatial decisions (Lopes and Begossi 2011). I showed that fishers make the majority of their fishing trips to preferred resource spaces. Preferred resource spaces vary from village to village, but fishers from the same village or who share social ties tend to fish at the same preferred resource space. Safety is the pivotal factor in choosing fishing locations, and only a minority of fishers will fish in places that they consider unsafe. Safety thus acts as a constraint on fishers' spatial range; managers who have this insight can implement spatial regulations that are better matched to fishers' needs and that are subsequently more likely to be supported. More generally, it emphasizes that it is essential to understand the marine resource base from different users' perspectives (Burke 2001).

I showed that most of the time, sites identified as being suitable for protection by the PASI matched sites that were selected through a community consultation process. This suggests that the PASI can be used as a cost-saving and conflict avoidance tool. For example, managers can use the PASI to identify sites for protection that fishers will likely support prior to approaching communities with a zoning proposal. This can minimize the number of face to face meetings and also speed up the consultation process for zoning marine protected areas.

The PASI was tailored for data-poor conditions that are so often characteristic of developing country fisheries. In light of the push to create networks of MPAs in regions such as the Coral Triangle, where areas of high biodiversity coincide with highly resource-dependent communities, the PASI can be used for rapidly assessing suitable sites for protection without committing too much time or money towards data collection.

## 6.3 Assumptions and limitations of study

The empirical study of fishers' spatial behaviour in Chapter 2 relied on catch logs covering 15 months in 2007-2008 and interviews from two separate points in time. The catch logs may have presented a biased picture of fishing behaviour if: i) the 15 month period had unusually high or low levels of fish catches and net revenues earned; or ii) sampled fishers who participated in the catch log programme and interviews were not representative of fishers in general.

I addressed (i) by comparing average catch and net revenue values from catch logs with those reported by fishers from a larger sample of interviews conducted in 2009. Analysis of variance showed no significant difference in the means of both data sets, so catch and net revenue data from catch logs can be assumed to be reflective of normal condition. During interviews, fishers' own perceptions of catch levels at a site may have been biased, as humans retrieve information of past conditions not by remembering individual events but by engaging 'shortcut'cognitive heuristics (Tversky and Kaneman 1974). Thus, fishers tend to remember unusually high catches in the past (Daw 2008b) and use those as benchmarks for gauging present catch levels, such that current catches may be judged to be lower than they are. Nonetheless, the ANOVA test showed that fishers' reported catch and net revenue levels were close to actual levels. Extracting information from a combination of research methods can thus overcome the inherent biases that may emerge from relying on either catch logs or interviews alone.

To mitigate the potential effect of (ii), I selected sites to provide a wide geographical coverage of fishing villages in Banggi and Semporna, as well as to provide a comprehensive representation of the different types of fishing (as driven by gear preference, ethnic background, access to markets etc.) that take place in both locations.

The PASI is driven by rules that govern fishers' spatial preferences, therefore the reliability of the PASI is based on the assumption that fishers' preferences will not change. Studies suggest that fishers tend not to deviate from accustomed fishing habits (Holland & Sutinen 2000), and remain loyal to their fishing grounds through time (Begossi 2006, McKenna et al. 2008). As such, I cautiously assume that preferences will remain stable through time as well. However, if fishers' preferences do change, the change can be accommodated in the PASI by adjusting the definition of linguistic categories and by modifying heuristic rules.

The PASI estimates site suitability scores based on the rationale that it is better to protect places where fishers do not go to fish, and that compliance is the desired outcome. The rationale is based on the assumption that all fishers fish within a preferred resource space, that is, a limited spatial range, such as demonstrated in Chapter 2, and that fishers generally are not willing to travel beyond this spatial range. The assumption would break down when different stakeholders, such as commercial fishing vessels, whose spatial movements are not bounded to preferred resource spaces, are brought into consideration. Then, another set of rules would have to be designed to accommodate that particular group's needs. This should not be taken as a weakness of the PASI; rather, it can be viewed as an opportunity for future expansion of the PASI to include more stakeholders.

A limitation of the PASI is that it can only assess sites one at a time, and does not address issues like connectivity or complementarity of sites to one another. Nonetheless, PASI output scores can be re-used as input into other spatial planning models such as Marxan, which do carry out those operations. The intention of the PASI was for rapid assessment of sites under situations where there is limited scientific knowledge about biodiversity and fisheries conditions. The quality of inputs to any model dictate the quality of output; in data poor conditions, site suitability outcomes estimated by the PASI's heuristic rules can be more informative than the output from a poorly developed spatial model.

## 6.4 Future directions

There is consensus that successful fisheries/marine resource management has to involve understanding and managing fishers' behaviour. While this study has contributed a snapshot of small-scale fishers' spatial use patterns, it would be interesting to monitor how fishers' perceptions, and consequently their fishing patterns, evolve as environmental and socio-economic conditions change in the long term. Such a study can also provide information on how resilient fishers are to change – this can help managers to anticipate how fishers will react to external change factors, and have in place mechanisms to facilitate fishers' adaptation to phenomena such as climate change. Furthermore, it would be useful to expand this study to include small-scale fishers in other ecosystems, as well as to commercial fishers, to assess the applicability of the conclusions on fishers' spatial behaviour to fishers in general.

Compliance with spatial regulations is an overarching goal of the PASI, and in the future, it would be useful and necessary to test whether PASI recommended sites actually met with compliance. Obtaining community feedback by presenting the PASI output to fishers and other marine stakeholders in Banggi could be a means of validating the appropriateness of PASI recommended sites. As well, a pilot study could be set up, in which one PASI recommended site is closed to fishing and subsequently monitored for compliant behaviour.

Given that compliant behaviour is central to fisheries and marine protected area management (Kelleher et al. 1995), future research should also emphasize more on this behavioural outcome as a measure of MPA success. Finally, future improvements to the PASI can include expanding the model's ability to encompass the preferences of stakeholders other than fishers, and to build a user friendly interface so that it can be easily accessible to users.

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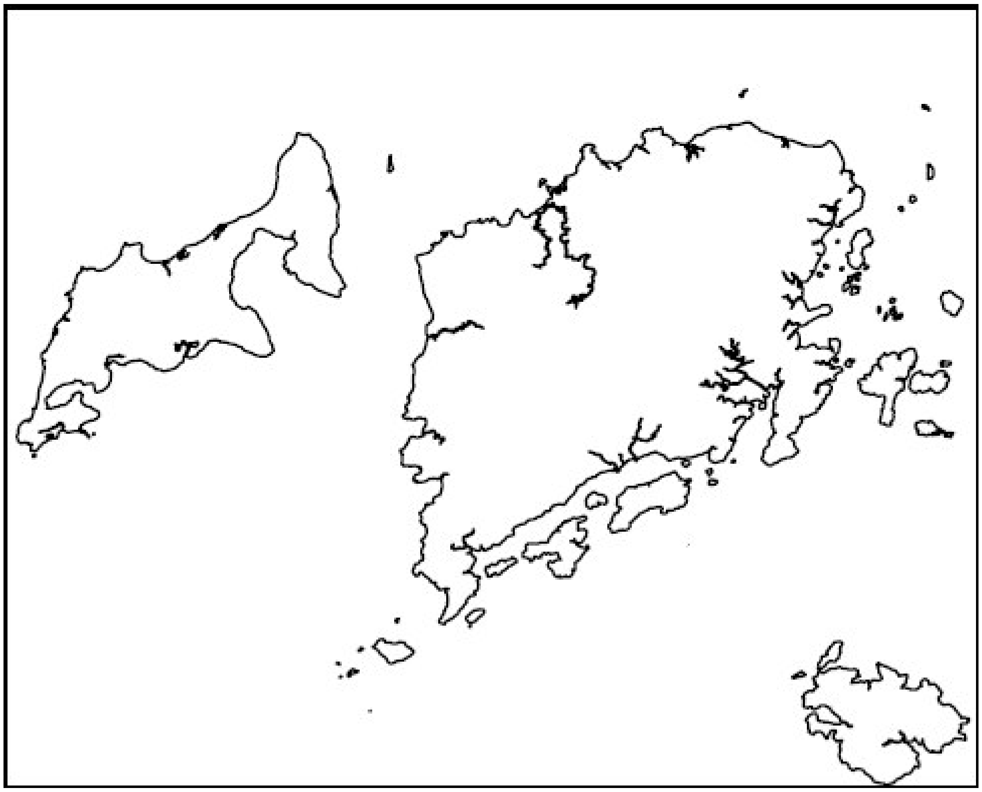
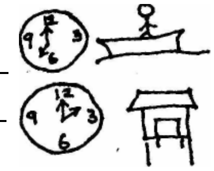
# Appendices

**Appendix A** Paper map used in interviews



**Appendix B** Catch log form



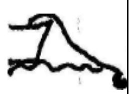
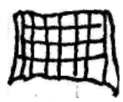
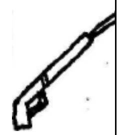
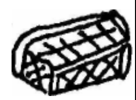
**MASA KELUAR:** ___:___

**KAMPUNG:**________________________ **MASA BALIK:** ___:___

**TARIKH:** / /

**hari / bulan / tahun**

**ALAT:**

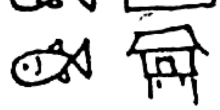
|  |  |  |  |  |  |  | |
|---|---|---|---|---|---|---|---|
| **Pancing** | **Hantuk** | **Tunda** | **Pukat** | **Panar** | **Bubu** | **Kutip** | **Lain__** |

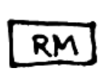
**TEMPAT TANGKAP IKAN**

| | | | |
|---|---|---|---|
| **Maliangin** | | **Balambangan** | |
| Belaruan | | Teluk Lung | |
| Tahitik | | Layang Layang | |
| Maliangin Kecil | | Simuanguak | |
| Linggan | | Tanjung Periuk | |
| Kawa kawa | | **Pegasaan** | |
| **Kobong** | | **Balak Balak** | |
| **Lumais** | | **Panukaran** | |
| **Lok Tohog** | | **Kuambang** | |
| **Batu Layar** | | **Manawali** | |
| **Patanunam** | | Naruntung | |
| **Sibogo** | | **Lain:** | |

**HARI INI…**

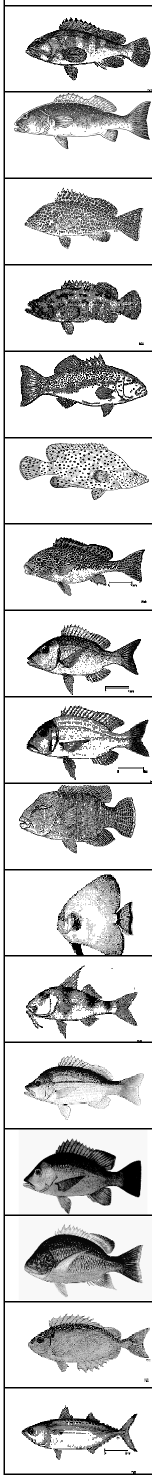
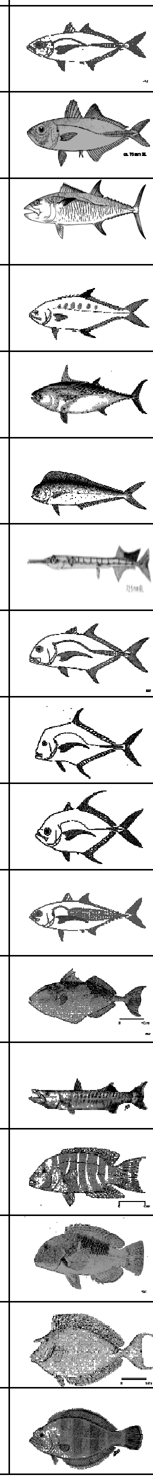
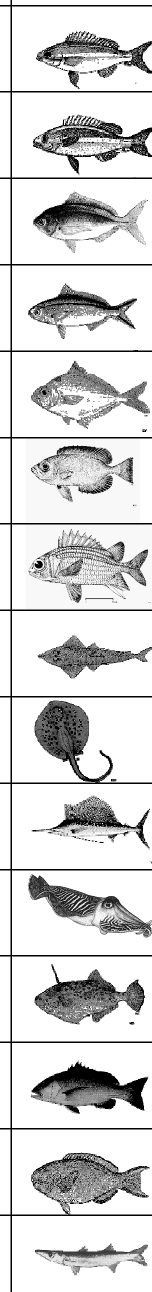
Jual berapa kilo ikan? [ ] KG 


Simpan berapa kilo ikan? [ ] KG 

Dapat berapa RM dari jualan ikan? [ ] RM 


Guna berapa banyak minyak? [ ] RM [ ] Gallon [ ] Litre 

## TANGKAPAN IKAN

| JENIS | BERAT (KG) | EKOR | JENIS IKAN | BERAT (KG) | EKOR | JENIS IKAN | BERAT | EKOR |
|---|---|---|---|---|---|---|---|---|
|  | | |  | | |  | | |
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**Appendix C** Questionnaire used for interviews in Sabah, Malaysia

ID____

1. Personal/Demographic

Name: Date:

Age: Gender:

Education: Primary/Secondary/None Ethnicity:

Kampung: Full-time/ Part-time:

## I. DEMOGRAPHIC INFORMATION

1. Where are you originally from?
2. How long have you lived in this village?____________
3. Why did you move to this village?

| | | |
|---|---|---|
| *Fishing* | *Other work* | *Family & friends* |
| Other | | |

4. Marital status: single___ married__
5. How many people live in your house? _______

| | | | |
|---|---|---|---|
| Adult male | Adult female | Male children | Female children |

## II. FISHING ACTIVITY

1. How many years have you been fishing?
2. Do you fish by yourself or with someone else?

| | | | | |
|---|---|---|---|---|
| FISH ALONE | | | | |
| WITH SOMEONE | 1 other | 2 other | 3 other | > 3 others |

3. Do you own your own boat?

| | | | | |
|---|---|---|---|---|
| YES: | Pumbot / sangkut | HP: | Length: | Age: |
| NO: | Owner is:<br>Pay rent? Y/N | Friend<br>RM_____per day/week/month | Family | |

*Gear, catch, effort*

4. What fishing gears do you use?

5. After listing gears: Please rank the gears according to which is most important

6. How many days per week do you use each gear? (low and high)

7.How much fish do you catch with xxx gear a day? We know that the amount of fish you catch is different each day, but say on a good day, how much fish would you catch? On a bad day? On an average day?

8. How many hours do you fish each day during bad, good, average day?

9. How many times do you go out each day?

10. For each gear you use, what % of your catch consists of ikan batu, tengirri, tulai/rumahan/termanung, sunnoh, ikan putih etc.

11. Do you fish from your village all year? Y/N

| Fishing location | Months | Gear |
|---|---|---|
| Village | | |
| Other ___________________ | | |

| Gear | Rank | Days per week (Low) | Days per week (High) | Bad catch (kg/day)/ season | Good catch (kg/day)/ season | Average catch (kg/day) / season | No. Hrs Good/ no. times per day | No. Hrs Bad/no. times per day | No. Hrs Average/ no. times per day | No. Ppl in household who use gear |
|---|---|---|---|---|---|---|---|---|---|---|
| Pancing | | | | / | / | / | / | / | / | |
| Hantuk | | | | / | / | / | / | / | / | |
| Tunda | | | | / | / | / | / | / | / | |
| Pukat (specify type) | | | | / | / | / | / | / | / | |
| Bubu | | | | / | / | / | / | / | / | |
| Panar | | | | / | / | / | / | / | / | |
| Cast net | | | | / | / | / | / | / | / | |
| Prong (sotong) | | | | / | / | / | / | / | / | |
| Gleanin g | | | | / | / | / | / | / | / | |
| Other | | | | / | / | / | / | / | / | |

Catch composition (%)

| Gear | Ikan batu | Sunnoh (hidup) | Putih | Tengirri | Termanung/tulai/ rumahan | Other |
|---|---|---|---|---|---|---|
| Pancing | | | | | | |
| Hantuk | | | | | | |
| Tunda | | | | | | |
| Pukat | | | | | | |
| Bubu | | | | | | |
| Panar | | | | | | |
| Cast net | | | | | | |
| Prong (sotong) | | | | | | |
| Gleaning | | | | | | |
| Other | | | | | | |

## III. ECONOMIC

*Fishing Income*

1. How much of the fish that you catch per day is kept for food, and how much is sold?

| Kept (% or kg) | Sold (% or kg) |
|---|---|
| | |

2a. How many years have you been catching fish to sell?

2b. Before that did you fish for food, or not fish at all?

3a. Which species do you sell?

3b. What is your daily/weekly income from selling fish and other marine resources?

| | Income/day/ week/month (Good) | Net? | Which months? | Income/day/ week/month (Bad) | Net? | Which months? |
|---|---|---|---|---|---|---|
| Ikan mati | | | | | | |
| Ikan hidup | | | | | | |
| Sotong | | | | | | |
| Balat / lepas | | | | | | |
| Other | | | | | | |

4. What is your fishing cost per month for fishing gear, fuel, and boat maintenance?

*Occupations (Occupational multiplicity)*

1. How many people in your household work?

2. What jobs do you and other members of your household do to earn money or bring food for the family? Fill in Table

| ACTIVITY | Check if applicable | No. of People | Rank of Importance | Notes/Detail |
|---|---|---|---|---|
| Fishing | | | | |
| Gleaning | | | | |
| Seaweed | | | | |
| Grocery/coffee shop | | | | |
| Farming | | | | |
| Food stall | | | | |
| Salaried Employment ___________________ | | | | |
| Tourism | | | | |
| Informal Economic Activities | | | | |
| Remittance from family | | | | |
| Other | | | | |

3. Occupational mobility: What other work have you done in the last 5 years?

| Occupation | Main job | Why stop? | Could get similar now? (y/n) | Prefer to current activity? (y/n) |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

*Household income and expenditure*

1. What is total household income from all family members per month? (net?)
2. What is household expenditure per week/ per month? (if cannot answer, then what is your expenditure in the past 2 weeks?)

| Income | Time (Week/month) | Expenditure | Week/month |
|---|---|---|---|
| | | | |

3. Do you have access to credit? (If you have to borrow money to buy fishing gear, food, etc., who do you borrow from?)

No (don't borrow) ____ Fish middleman ____ Store owner ____

Family/friends _____ Bank/financial institution ____ Co-operative____

4a. If have access to credit: Do you repay your money with interest? Y/N

4b. How much interest do you have to pay?

5a. Do you have any savings? Y/N

5b. On average, how much (% or RM) of your monthly fishing income can you save?

## IV. SPATIAL ATTRIBUTES

1. What are the types of fish that you like to catch? List the top 3 preferred species

2. Where can you catch a lot of the fish you like?

3. How many times a week do you go to those fishing sites where you can catch the fish you like?

| Species | Location caught | Fishing frequency at location (# of times/week) |
|---|---|---|
| 1. | a.<br>b. | |
| 2. | a.<br>b. | |
| 3. | a.<br>b. | |

4. Which areas have the most fish (most productive)? How do you know?

| Name of productive fishing ground(s) | Productive cue | Do you fish at productive area? | Fishing frequency (# times per week/ month) |
|---|---|---|---|
| | | | |

5. Think of all the years you have been fishing in this area. Has there been any change in the productivity of this area?

Prompt: seasonal/ cyclical changes to productivity

6. If so, have you changed your fishing to go where the productive areas are?

*Safety*

1. How important is personal safety to your choice of fishing grounds?

| Not important | A little bit important | Important | Very important |
|---|---|---|---|
| | | | |

2. Which areas are considered to be safe for fishing? How often do you go there?

3. Which areas are considered to be unsafe for fishing? How often do you go there?

| Fishing ground | Safe | Very safe | Somewhat unsafe | Very unsafe | Fishing frequency (# times /week) |
|---|---|---|---|---|---|
| | | | | | |

4. If you go to a fishing site and there are outsider boats there that you don't recognise, will you fish there by yourself?

5. Are there fishing grounds that are used frequently by outsiders? How many outsider boats do you usually see in one day?

6. Is there a place that you don't like to fish at? Why?

*Fisher mobility*

1a. At how many fishing grounds do you spend the majority of your fishing time?

b. Which is the fishing ground that you spend the most time at?

c. How many times a week / month do you fish there? What proportion (%) of your total fishing time do you spend fishing at this fishing ground?

| # of fishing grounds | 1 | 1-3 | 3-4 | 4-6 | >6 |
|---|---|---|---|---|---|
| | (   ) | (   ) | (   ) | (   ) | (   ) |

| Most frequented fishing grounds | Frequency | | Revenue | | Catch | | Distance | |
|---|---|---|---|---|---|---|---|---|
| | # of times per week / month | % of total fishing time | RM/ trip | Perceived condition | Kg/ trip | Perceived condition | Km | Perceived condition |
| 1. | | | | | | | | |
| 2. | | | | | | | | |
| 3. | | | | | | | | |
| 4. | | | | | | | | |
| 5. | | | | | | | | |

2. Pretend that a new regulation says that [your most frequented fishing ground] is closed off. What would you do?

i) go to another fishing ground ii) get another job iii) continue fishing

*Fisheries perceptions (fill in using Fisher Mobility table)*

1a. How much income can you usually get from one day of fishing there?

1b. In your opinion, is that considered to be low / med / hi?

2a. How many kilos of fish can you usually get from one day of fishing there?

2b. In your opinion, is that considered to be low/ med/ hi?

3a. What is the distance of that location from your kampung?

3b. In your opinion, is that considered to be low/ med/ hi?

4. If petrol was cheaper/ more available, would you go to different fishing grounds?

Yes _____ No _____

5. If you had a bigger boat, would you go to different fishing grounds?

Yes _____ No _____

## V. CAPACITY TO ADAPT

*Capacity to anticipate change and develop response*

1a. If you were to get 20% less catch <u>all year</u>, what would you do?

| | | | | | |
|---|---|---|---|---|---|
| keep fishing at same amount | Fish harder | Fish less | move locations | change gear | leave fishery- where to? |
| Other | | | | | |

If keep fishing, for how long?

1b. if you were to get 50% less catch <u>all year</u> what would you do?

| | | | | | |
|---|---|---|---|---|---|
| keep fishing at same amount | fish harder | Fish less | move locations | change gear | leave fishery- where to? |
| Other | | | | | |

If keep fishing, for how long?

*Causality & intervention – perception of link between humans and marine environment*

1. Is there more or less fish on the reef now compared to 5 years ago?
2. How do you know there are more/less fish now?
3. What do you think caused there to be more/less fish? (causality)
4. What can be done around here (kampung/Banggi) to increase the number of fish on the reef? (intervention)

Possible responses (Tick if any are mentioned):

a) restrict gear ______ b) stop fish bombing ______ c) ban commercial vessels ______

d) control migrants ______

## **Appendix D** VBA code for operating the protected area suitability index (PASI)

```
Option Explicit
    '## Declare output membership variables ##
    Public SuitabilityVeryHigh(16) As Double
    Public SuitabilityHigh(13) As Double, SuitabilityModerate(9) As Double
    Public SuitabilityLow(12) As Double
    Public SuitabilitySpawn As Double
    Public OutputValueP(3) As Double
    Public OutputValueC(3) As Double
    Public OutputValue(3) As Double
    Public WeightedOutputValue(1) As Double
    Public WeightedUpperValue(1) As Double
    Public WeightedLowerValue(1) As Double
    Public WeightedOutputProb1(1) As Double
    Public WeightedOutputProb2(1) As Double
    Public WeightedOutputProb3(1) As Double
    Public WeightedOutputProb4(1) As Double
    '=====================================================================
    'Rules weights
    Public AvgcatchLowWeight As Double
    Public AvgcatchModerateWeight As Double
    Public AvgcatchHighWeight As Double
    Public DistVeryFarWeight As Double
    Public DistFarWeight As Double
    Public DistNearWeight As Double
    Public DistVeryNearWeight As Double
    Public DepthVeryDeepWeight As Double
    Public DepthDeepWeight As Double
    Public DepthLittleDeepWeight As Double
    Public DepthShallowWeight As Double
    Public RevLowWeight As Double
    Public RevMediumWeight As Double
    Public RevHighWeight As Double
    Public RevVeryHighWeight As Double
    Public BoatsFewWeight As Double
    Public BoatsModerateWeight As Double
    Public BoatsManyWeight As Double
    Public EndSpeciesSeldomWeight As Double
    Public EndSpeciesSometimesWeight As Double
    Public EndSpeciesOftenWeight As Double
    Public CorcovPoorWeight As Double
    Public CorcovFairWeight As Double
    Public CorcovGoodWeight As Double
```

```
 Public CorcovExcellentWeight As Double
 Public FishcountPoorWeight As Double
 Public FishcountFairWeight As Double
 Public FishcountGoodWeight As Double
 Public FishcountExcellentWeight As Double
 Public RevVHighDistVFarWeight As Double
 Public AvgcatchHighDistVFarWeight As Double
 Public RevHighDistVFarWeight As Double
 Public AvgcatchModerateDistVFarWeight As Double
 Public Spawningweight As Double
 Public SeagrassWeight As Double
‘==================================================================
 'Output Fuzzy Membership Function parameters
Public SuitVeryHigh(1 To 4) As Double 'Output FMF for Very high suitability
Public SuitHigh(1 To 4) As Double 'OutputFMF for High suitability
Public SuitModerate(1 To 4) As Double 'OutputFMF for Moderate Resilience
Public SuitLow(1 To 4) As Double 'OutputFMF For Very Low Resilience
Public AlphaCutOutput(1 To 4) As Double
Public OutputFMFShape(4) As Integer
Public ProbP(4) As Double ' 1= High, 2=Moderate, 3=low, 4=very low
Public ProbC(4) As Double ' 1= High, 2=Moderate, 3=low, 4=very low
Public Prob(4) As Double ' 1= High, 2=Moderate, 3=low, 4=very low
Public Centroid(4) As Double 'Centroid for output FMFs
Public UpperCentroid(4) As Double 'Upper limits of the output sets for calculation of CL
Public LowerCentroid(4) As Double ' Lower limits of output sets for calculation of CL
Public InputFMFShape(4) As Integer
Public FishingNumber As Integer

 ' ## Read rules weights from worksheet “Rules” ##
 Sub Readweights()
 With Worksheets("Rules")
 AvgcatchLowWeight = .Cells(2, 10).Value
 AvgcatchModerateWeight = .Cells(3, 10).Value
 AvgcatchHighWeight = .Cells(4, 10).Value
 DistVeryFarWeight = .Cells(6, 10).Value
 DistFarWeight = .Cells(7, 10).Value
 DistNearWeight = .Cells(8, 10).Value
 DistVeryNearWeight = .Cells(9, 10).Value
 DepthVeryDeepWeight = .Cells(10, 10).Value
 DepthDeepWeight = .Cells(11, 10).Value
 DepthLittleDeepWeight = .Cells(13, 10).Value
 DepthShallowWeight = .Cells(14, 10).Value
 RevLowWeight = .Cells(16, 10).Value
```

```
    RevMediumWeight = .Cells(17, 10).Value
    RevHighWeight = .Cells(18, 10).Value
    RevVeryHighWeight = .Cells(19, 10).Value
    BoatsFewWeight = .Cells(21, 10).Value
    BoatsModerateWeight = .Cells(22, 10).Value
    BoatsManyWeight = .Cells(23, 10).Value
    EndSpeciesSeldomWeight = .Cells(24, 10).Value
    EndSpeciesSometimesWeight = .Cells(29, 10).Value
    EndSpeciesOftenWeight = .Cells(34, 10).Value
    CorcovPoorWeight = .Cells(38, 10).Value
    CorcovFairWeight = .Cells(39, 10).Value
    CorcovGoodWeight = .Cells(40, 10).Value
    CorcovExcellentWeight = .Cells(41, 10).Value
    FishcountPoorWeight = .Cells(42, 10).Value
    FishcountFairWeight = .Cells(43, 10).Value
    FishcountGoodWeight = .Cells(44, 10).Value
    FishcountExcellentWeight = .Cells(45, 10).Value
    RevVHighDistVFarWeight = .Cells(19, 10).Value
    AvgcatchHighDistVFarWeight = .Cells(5, 10).Value
    RevHighDistVFarWeight = .Cells(20, 10).Value
    AvgcatchModerateDistVFarWeight = .Cells(5, 10).Value
    Spawningweight = .Cells(47, 10).Value
    SeagrassWeight = .Cells(48, 10).Value
End With
End Sub

'##Fuzzification process: read inputs and assign fuzzy membership doa based on specified membership shape##
Function Fuzzify(Domain_values As Double, FMF_Shape As Integer, parameter_a As Double, parameter_b As Double, _
parameter_c As Double, Optional parameter_d As Double, Optional alphacut As Double)
    If Domain_values <> 0 Then
        Select Case FMF_Shape
            Case 1  'Trapezoid distribution
                Fuzzify = trapezoid(Domain_values, parameter_a, parameter_b, parameter_c, parameter_d)
            Case 2 'Triangle distribution
                Fuzzify = Triangle(Domain_values, parameter_a, parameter_b, parameter_c)
            Case 3  'Logistic decline distribution
                Fuzzify = Logistic_D(Domain_values, parameter_a, parameter_b, parameter_c)
            Case 4  'Logistic growth distribution
                Fuzzify = Logistic_G(Domain_values, parameter_a, parameter_b, parameter_c)
        End Select
        If Fuzzify <= alphacut Then Fuzzify = 0
    End If
End Function
```

```
'=================================================================================
'## Defuzzification process ##
Function DeFuzzify(Domain_values As Double, FMF_Shape As Integer, parameter_a As Double, parameter_b As Double, _
parameter_c As Double, Optional parameter_d As Double, Optional alphacut As Double)
  If Domain_values <> 0 Then
    Select Case FMF_Shape
      Case 1  'Trapezoid distribution
        DeFuzzify = trapezoid(Domain_values, parameter_a, parameter_b, parameter_c, parameter_d)
      Case 2 'Triangle distribution
        DeFuzzify = Triangle(Domain_values, parameter_a, parameter_b, parameter_c)
      Case 3  'Logistic decline distribution
        DeFuzzify = Logistic_D(Domain_values, parameter_a, parameter_b, parameter_c)
      Case 4  'Logistic growth distribution
        DeFuzzify = Logistic_G(Domain_values, parameter_a, parameter_b, parameter_c)
    End Select
    If DeFuzzify > alphacut Then DeFuzzify = alphacut
 End If
End Function
'=============================================================================
'Centroid calculation
Function FuzzCentroid(FMF_Shape As Integer, parameter_a As Double, parameter_b As Double, _
parameter_c As Double, Optional parameter_d As Double, Optional alphacut As Double)
  Select Case FMF_Shape
    Case 1  'Trapezoid distribution declining
        'If parameter_b = 0 And parameter_a = 0 Then
          'FuzzCentroid = parameter_c
        'Else
          FuzzCentroid = (parameter_b + parameter_c) / 2
        'End If
    Case 2  'Trapezoid distribution increasing
      FuzzCentroid = parameter_b
    Case 3 'Triangle distribution
      FuzzCentroid = parameter_b
  End Select
End Function

'Subroutine that i) reads parameter values ii)fuzzifies iii)calculates centroid iv)defuzzifies and produces final suitability score
Sub Main
  '## Declare Input parameters
  '=========================================================================
  ' Average catch at site
  Dim AvgCatchDomain As Double 'Average catch obtained at site
  Dim AvgCatch(1 To 3, 1 To 4) As Double ' 1=low, 2=moderate, 3=high
```

```
Dim AlphaCutAvgCatchInput(1 To 3) As Double ' 1=low, 2=moderate, 3=high
Dim InputAvgCatchFMFShape(3) As Integer
Dim AntecedentAvgCatch(3) As Double ' 1=low, 2=moderate, 3=high
'=========================================================================
'Distance from nearest village
Dim DistDomain As Double 'Distance from nearest village
Dim Dist(1 To 4, 1 To 4) As Double '1=very far, 2=far, 3=near, 4=very near
Dim AlphaCutDistInput(1 To 4) As Double
Dim InputDistFMFShape(4) As Integer
Dim AntecedentDist(4) As Double '1=very far, 2=far, 3=near, 4=very near
'=========================================================================
'Depth of site
Dim DepthDomain As Double 'Depth at site
Dim Depth(1 To 4, 1 To 4) As Double '1=very deep, 2=deep, 3=little deep, 4=shallow
Dim AlphaCutDepthInput(1 To 4) As Double
Dim InputDepthFMFShape(4) As Integer
Dim AntecedentDepth(4) As Double '1=very deep, 2=deep, 3=little deep, 4=shallow
'=========================================================================
'Revenue at site
Dim RevDomain As Double 'Revenue obtained at site
Dim Rev(1 To 4, 1 To 4) As Double '1=low, 2=moderate, 3=moderately high, 4=high
Dim AlphaCutRevInput(1 To 4) As Double
Dim InputRevFMFShape(4) As Integer
Dim AntecedentRev(4) As Double '1=low, 2=moderate, 3=moderately high, 4=high
'=========================================================================
'Crowding
Dim BoatsDomain As Double   'Number of boats fishing at site
Dim Boats(1 To 3, 1 To 4) As Double '1=few, 2=moderate, 3=many
Dim AlphaCutBoatsInput(3) As Double
Dim InputBoatsFMFShape(3) As Integer
Dim AntecedentBoats(3) As Double
'========================================================================
'Sighting : Endangered Species
Dim EndSpeciesDomain As Double 'Frequency of sighting turtle
Dim EndSpecies(1 To 3, 1 To 4) As Double '1=seldom, 2=sometimes, 3=often
Dim AlphaCutEndSpeciesInput(1 To 3) As Double
Dim InputEndSpeciesFMFShape(3) As Integer
Dim AntecedentEndSpecies(3) As Double '1=seldom, 2=sometimes, 3=often
'========================================================================
'Coral cover
Dim CorcovDomain As Double  'Percentage coral cover at site
Dim Corcov(1 To 4, 1 To 4) As Double '1=poor, 2=fair, 3=good, 4=excellent
Dim AlphaCutCorcovInput(1 To 4) As Double
```

```
Dim InputCorcovFMFShape(4) As Integer
Dim AntecedentCorcov(4) As Double '1=poor, 2=fair, 3=good, 4=excellent
'========================================================================
'Fish abundance
Dim FishcountDomain As Double   'Fish count at site
Dim Fishcount(1 To 4, 1 To 4) As Double '1=poor, 2=fair, 3=good, 4=excellent
Dim AlphaCutFishcountInput(1 To 4) As Double
Dim InputFishcountFMFShape(4) As Integer
Dim AntecedentFishcount(4) As Double '1=poor, 2=fair, 3=good, 4=excellent
'========================================================================
'Spawning
Dim SpawningDomain As Double
Dim Spawning(2, 1 To 4) As Double   '1= no spawning    2=spawning
Dim AlphaCutSpawningInput(2) As Double
Dim InputSpawningFMFShape(2) As Integer
Dim AntecedentSpawning(2) As Double
'========================================================================
 'Seagrass
Dim SeagrassDomain As Double
Dim Seagrass(2, 1 To 4) As Double   '1= no seagrass    2=seagrass
Dim AlphaCutSeagrassInput(2) As Double
Dim InputSeagrassFMFShape(2) As Integer
Dim AntecedentSeagrass(2) As Double
'========================================================================
Dim sum As Double, sumP As Double, sumC As Double, sumPC As Double
Dim ConfSuit As Double ' Acceptable confidence level of output
Dim i As Integer, j As Integer
'========================================================================
'## Reading from worksheet FMF, parameters to define input ##
'========================================================================
Call ReadInputFMF(4, 1, 3, AvgCatch(), AlphaCutAvgCatchInput(), InputAvgCatchFMFShape()) '##Catch
Call ReadInputFMF(15, 1, 4, Dist(), AlphaCutDistInput(), InputDistFMFShape()) '##Distance
Call ReadInputFMF(28, 1, 4, Depth(), AlphaCutDepthInput(), InputDepthFMFShape()) '##Depth
Call ReadInputFMF(41, 1, 4, Rev(), AlphaCutRevInput(), InputRevFMFShape()) '## revenue
Call ReadInputFMF(54, 1, 3, Boats(), AlphaCutBoatsInput(), InputBoatsFMFShape()) '## # of boats
Call ReadInputFMF(60, 1, 3, EndSpecies(), AlphaCutEndSpeciesInput(), InputEndSpeciesFMFShape()) '## Sighting
frequency of Endangered Species
Call ReadInputFMF(90, 1, 4, Corcov(), AlphaCutCorcovInput(), InputCorcovFMFShape()) '## Coral cover
Call ReadInputFMF(97, 1, 4, Fishcount(), AlphaCutFishcountInput(), InputFishcountFMFShape()) '## Fish abundance
Call ReadInputFMF(104, 1, 2, Spawning(), AlphaCutSpawningInput(), InputSpawningFMFShape()) 'Presence of spawning
can delete?
Call ReadInputFMF(109, 1, 2, Seagrass(), AlphaCutSeagrassInput(), InputSeagrassFMFShape()) 'Presence of seagrass   can
delete?
```

```
'=======================================================================
    '## Reading parameters to define output FMF
'=======================================================================
    FishingNumber = Worksheets("main").Range("FishNum").Value
    ConfSuit = Worksheets("main").Range("confsuit").Value

For i = 1 To FishingNumber
    '=======================================================================
    'Fuzzy reasoning routine
    '=======================================================================
    'Reset values to 0
        For j = 1 To 3
        OutputValueP(j) = 0
        OutputValueC(j) = 0
        OutputValue(j) = 0
    Next j
    With Worksheets("defuzzyfmf")
        For j = 1 To 4
                SuitVeryHigh(j) = .Cells(3, 2 + j).Value
                SuitHigh(j) = .Cells(4, 2 + j).Value
                SuitModerate(j) = .Cells(5, 2 + j).Value
                SuitLow(j) = .Cells(6, 2 + j).Value
                OutputFMFShape(j) = .Cells(2 + j, 2).Value
                AlphaCutOutput(j) = .Cells(8 + j, 2)
         Next j
    End With
    For j = 1 To 2
        SuitabilitySpawn = 0
        AntecedentSeagrass(j) = 0
    Next j
    For j = 1 To 3
        AntecedentAvgCatch(j) = 0: AntecedentBoats(j) = 0
        AntecedentEndSpecies(j) = 0
    Next j
    For j = 1 To 4
        AntecedentDist(j) = 0: AntecedentDepth(j) = 0
        AntecedentRev(j) = 0
        AntecedentCorcov(j) = 0: AntecedentFishcount(j) = 0
    Next j
    For j = 1 To 9
        SuitabilityModerate(j) = 0
    Next j
    For j = 1 To 12
```

```
        SuitabilityLow(j) = 0
    Next j
    For j = 1 To 13
        SuitabilityHigh(j) = 0
    Next j
    For j = 1 To 16
        SuitabilityVeryHigh(j) = 0
    Next j

'=====================================================================
'Read domain values
'=====================================================================
    If Worksheets("main").Cells(1 + i, 5).Value = "" Then AvgCatchDomain = 0 Else AvgCatchDomain =
Worksheets("main").Cells(1 + i, 5).Value
    If Worksheets("main").Cells(1 + i, 6).Value = "" Then DistDomain = 0 Else DistDomain = Worksheets("main").Cells(1 + i,
6).Value
    If Worksheets("main").Cells(1 + i, 7).Value = "" Then DepthDomain = 0 Else DepthDomain = Worksheets("main").Cells(1 +
i, 7).Value
    If Worksheets("main").Cells(1 + i, 8).Value = "" Then RevDomain = 0 Else RevDomain = Worksheets("main").Cells(1 + i,
8).Value
    If Worksheets("main").Cells(1 + i, 9).Value = "" Then BoatsDomain = 0 Else BoatsDomain = Worksheets("main").Cells(1 + i,
9).Value
    If Worksheets("main").Cells(1 + i, 10).Value = "" Then EndSpeciesDomain = 0 Else EndSpeciesDomain =
Worksheets("main").Cells(1 + i, 10).Value
    If Worksheets("main").Cells(1 + i, 15).Value = "" Then CorcovDomain = 0 Else CorcovDomain =
Worksheets("main").Cells(1 + i, 15).Value
    If Worksheets("main").Cells(1 + i, 16).Value = "" Then FishcountDomain = 0 Else FishcountDomain =
Worksheets("main").Cells(1 + i, 16).Value
    If Worksheets("main").Cells(1 + i, 17).Value = "" Then SpawningDomain = 0 Else SpawningDomain =
Worksheets("main").Cells(1 + i, 17).Value
    If Worksheets("main").Cells(1 + i, 18).Value = "" Then SeagrassDomain = 0 Else SeagrassDomain =
Worksheets("main").Cells(1 + i, 18).Value
 '=====================================================================
'fuzzifying the input domains
'=====================================================================
    '## For average catch
        If AvgCatchDomain <> 0 Then
            For j = 1 To 3
            AntecedentAvgCatch(j) = Fuzzify(AvgCatchDomain, InputAvgCatchFMFShape(j), AvgCatch(j, 1), AvgCatch(j, 2),
AvgCatch(j, 3), AvgCatch(j, 4), AlphaCutAvgCatchInput(j))
            Next j
        End If
    '## For # of boats
```

```
        If BoatsDomain <> 0 Then
          For j = 1 To 3
            AntecedentBoats(j) = Fuzzify(BoatsDomain, InputBoatsFMFShape(j), Boats(j, 1), Boats(j, 2), Boats(j, 3), Boats(j, 4),
AlphaCutBoatsInput(j))
          Next j
        End If
      '## Distance to closest village
        If DistDomain <> 0 Then
           For j = 1 To 4
             AntecedentDist(j) = Fuzzify(DistDomain, InputDistFMFShape(j), Dist(j, 1), Dist(j, 2), Dist(j, 3), Dist(j, 4),
AlphaCutDistInput(j))
           Next j
        End If
      '## Depth
        If DepthDomain <> 0 Then
          For j = 1 To 4
            AntecedentDepth(j) = Fuzzify(DepthDomain, InputDepthFMFShape(j), Depth(j, 1), Depth(j, 2), Depth(j, 3), Depth(j,
4), AlphaCutDepthInput(j))
          Next j
        End If
      '## Revenue
        If RevDomain <> 0 Then
          For j = 1 To 4
            AntecedentRev(j) = Fuzzify(RevDomain, InputRevFMFShape(j), Rev(j, 1), Rev(j, 2), Rev(j, 3), Rev(j, 4),
AlphaCutRevInput(j))
          Next j
        End If
       '## For sighting of turtle
        If EndSpeciesDomain <> 0 Then
          For j = 1 To 3
            AntecedentEndSpecies(j) = Fuzzify(EndSpeciesDomain, InputEndSpeciesFMFShape(j), EndSpecies(j, 1),
EndSpecies(j, 2), EndSpecies(j, 3), EndSpecies(j, 4), AlphaCutEndSpeciesInput(j))
          Next j
        End If
      '## Coral cover
        If CorcovDomain <> 0 Then
          For j = 1 To 4
            AntecedentCorcov(j) = Fuzzify(CorcovDomain, InputCorcovFMFShape(j), Corcov(j, 1), Corcov(j, 2), Corcov(j, 3),
Corcov(j, 4), AlphaCutCorcovInput(j))
          Next j
        End If
      '## Fish abundance
        If FishcountDomain <> 0 Then
```

```
        For j = 1 To 4
            AntecedentFishcount(j) = Fuzzify(FishcountDomain, InputFishcountFMFShape(j), Fishcount(j, 1), Fishcount(j, 2),
Fishcount(j, 3), Fishcount(j, 4), AlphaCutFishcountInput(j))
        Next j
    End If
  '## spawning
    If SpawningDomain <> 0 Then
        For j = 1 To 2
        AntecedentSpawning(j) = Fuzzify(SpawningDomain, InputSpawningFMFShape(j), Spawning(j, 1), Spawning(j, 2),
Spawning(j, 3), Spawning(j, 4), AlphaCutSpawningInput(j))
        Next j
    End If
  '## seagrass
    If SeagrassDomain <> 0 Then
        For j = 1 To 2
        AntecedentSeagrass(j) = Fuzzify(SeagrassDomain, InputSeagrassFMFShape(j), Seagrass(j, 1), Seagrass(j, 2), Seagrass(j,
3), Seagrass(j, 4), AlphaCutSeagrassInput(j))
        Next j
    End If
'=====================================================================
‘Bring up heuristic rules
    'Average Catch
    Call HeuristicAvgcatchLow(AntecedentAvgCatch(1), 0)
    Call HeuristicAvgcatchLow2(AntecedentAvgCatch(1), 0)
    'Call HeuristicAvgcatchModerate(AntecedentAvgCatch(2), 0)
    'Call HeuristicAvgcatchHigh(AntecedentAvgCatch(3), 0)
    'Distance from closest village
    Call HeuristicDistVeryFar(AntecedentDist(1), 0)
    Call HeuristicDistFar(AntecedentDist(2), 0)
    Call HeuristicDistFar2(AntecedentDist(2), 0)
    Call HeuristicDistNear(AntecedentDist(3), 0)
    Call HeuristicDistVeryNear(AntecedentDist(4), 0)
    'Depth
    Call HeuristicDepthVeryDeep(AntecedentDepth(1), 0)
    Call HeuristicDepthDeep(AntecedentDepth(2), 0)
    Call HeuristicDepthDeep2(AntecedentDepth(2), 0)
    Call HeuristicDepthLittleDeep(AntecedentDepth(3), 0)
    Call HeuristicDepthShallow(AntecedentDepth(4), 0)
    'Revenue
    Call HeuristicRevLow(AntecedentRev(1), 0)
    Call HeuristicRevMedium(AntecedentRev(2), 0)
    'Call HeuristicRevHigh(AntecedentRev(3), 0)
    'Call HeuristicRevVeryHigh(AntecedentRev(4), 0)
```

```
'Crowding
Call HeuristicBoatsFew(AntecedentBoats(1), 0)
Call HeuristicBoatsModerate(AntecedentBoats(2), 0)
Call HeuristicBoatsMany(AntecedentBoats(3), 0)
Call HeuristicBoatsMany2(AntecedentBoats(3), 0)
'Sightings Turtle
Call HeuristicEndSpeciesSeldom(AntecedentEndSpecies(1), 0)
Call HeuristicEndSpeciesSometimes(AntecedentEndSpecies(2), 0)
Call HeuristicEndSpeciesSometimes2(AntecedentEndSpecies(2), 0)
Call HeuristicEndSpeciesOften(AntecedentEndSpecies(3), 0)
'Coral cover
Call HeuristicCorcovPoor(AntecedentCorcov(1), 0)
Call HeuristicCorcovFair(AntecedentCorcov(2), 0)
Call HeuristicCorcovGood(AntecedentCorcov(3), 0)
Call HeuristicCorcovExcellent(AntecedentCorcov(4), 0)
'Fish count
Call HeuristicFishcountPoor(AntecedentFishcount(1), 0)
Call HeuristicFishcountFair(AntecedentFishcount(2), 0)
Call HeuristicFishcountGood(AntecedentFishcount(3), 0)
Call HeuristicFishcountExcellent(AntecedentFishcount(4), 0)
'Revenue Moderate and Distance VeryFar
Call HeuristicRevHighDistVFar(AntecedentRev(3), AntecedentDist(1), 0)
'Revenue VeryHigh and Distance VeryFar
Call HeuristicRevVHighDistVFar(AntecedentRev(4), AntecedentDist(1), 0)
'Catch High and Distance VeryFar
Call HeuristicAvgcatchHighDistVFar(AntecedentAvgCatch(3), AntecedentDist(1), 0)
'Catch Moderate and Distance VeryFar
Call HeuristicAvgcatchModerateDistVFar(AntecedentAvgCatch(2), AntecedentDist(1), 0)
'Seagrass
Call HeuristicSeagrass(AntecedentSeagrass(2), 0)
'Spawning
Call HeuristicSpawn2(AntecedentSpawning(2), 0)

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'Define SuitHi, Suitlow etc.
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'Calculation of Probs and centroids and defuzzification
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'Accumulating evidence (degree of association) for each suitability outcome of Very High, High, Moderate, Low

'Calculate PREFERENCE subcomponent
ProbP(1) = MYCIN(SuitabilityLow(1) * DistVeryFarWeight, SuitabilityLow(2) * DepthVeryDeepWeight, _
SuitabilityLow(3) * RevLowWeight, SuitabilityLow(11) * AvgcatchLowWeight, SuitabilityLow(12) * BoatsManyWeight)
```

```
ProbP(2) = MYCIN(SuitabilityModerate(1) * AvgcatchLowWeight, SuitabilityModerate(2) * DepthShallowWeight, _
SuitabilityModerate(3) * BoatsManyWeight, SuitabilityModerate(6) * RevHighDistVFarWeight, _
SuitabilityModerate(7) * AvgcatchModerateDistVFarWeight, SuitabilityModerate(8) * DistFarWeight)

ProbP(3) = MYCIN(SuitabilityHigh(1) * AvgcatchModerateWeight, SuitabilityHigh(2) * DistFarWeight, _
SuitabilityHigh(3) * RevMediumWeight, SuitabilityHigh(4) * BoatsModerateWeight, SuitabilityHigh(6) *
RevVHighDistVFarWeight, _ SuitabilityHigh(7) * AvgcatchHighDistVFarWeight, SuitabilityHigh(12) *
DepthDeepWeight)

ProbP(4) = MYCIN(SuitabilityVeryHigh(1) * AvgcatchHighWeight, SuitabilityVeryHigh(3) * DistVeryNearWeight, _
SuitabilityVeryHigh(4) * DepthDeepWeight, SuitabilityVeryHigh(7) * RevVeryHighWeight, SuitabilityVeryHigh(8) *
BoatsFewWeight, _SuitabilityVeryHigh(5) * DepthLittleDeepWeight, SuitabilityVeryHigh(2) * DistNearWeight,
SuitabilityVeryHigh(6) * RevHighWeight)

sumP = 0
For j = 1 To 4
   sumP = sumP + ProbP(j)
Next j

'Defuzzify Preference Prob
If sumP > 0 Then
   'calculation of suitability
   Call DefuzzCentroidP(ProbP(1), Centroid(1), ProbP(2), Centroid(2), _
   ProbP(3), Centroid(3), ProbP(4), Centroid(4), OutputValueP(1))
   'calculation of the upper limit
   Call DefuzzCentroidP(ProbP(1), UpperCentroid(1), ProbP(2), UpperCentroid(2), _
   ProbP(3), UpperCentroid(3), ProbP(4), UpperCentroid(4), OutputValueP(2))
   'calculation of the lower limit
   Call DefuzzCentroidP(ProbP(1), LowerCentroid(1), ProbP(2), LowerCentroid(2), _
   ProbP(3), LowerCentroid(3), ProbP(4), LowerCentroid(4), OutputValueP(3))

Worksheets("results").Cells(1 + i, 3).Value = Round(ProbP(1), 3)
Worksheets("results").Cells(1 + i, 4).Value = Round(ProbP(2), 3)
Worksheets("results").Cells(1 + i, 5).Value = Round(ProbP(3), 3)
Worksheets("results").Cells(1 + i, 6).Value = Round(ProbP(4), 3)
Worksheets("results").Cells(1 + i, 2).Value = Round(OutputValueP(1), 2)
Worksheets("results").Cells(1 + i, 7).Value = Round(OutputValueP(2), 2)
Worksheets("results").Cells(1 + i, 8).Value = Round(OutputValueP(3), 2)
End If

'Calculate CONSERVATION subcomponent
ProbC(1) = MYCIN(SuitabilityVeryHigh(9) * EndSpeciesOftenWeight, SuitabilityVeryHigh(14) * CorcovExcellentWeight,
```

```
_ SuitabilityVeryHigh(15) * FishcountExcellentWeight, SuitabilityVeryHigh(16) * SeagrassWeight)

ProbC(2) = MYCIN(SuitabilityHigh(5) * EndSpeciesSometimesWeight, SuitabilityHigh(10) * CorcovGoodWeight, _
SuitabilityHigh(11) * FishcountGoodWeight, SuitabilityHigh(13) * SeagrassWeight)

ProbC(3) = MYCIN(SuitabilityModerate(9) * EndSpeciesSometimesWeight, SuitabilityModerate(4) * CorcovFairWeight, _
SuitabilityModerate(5) * FishcountFairWeight)

ProbC(4) = MYCIN(SuitabilityLow(4) * EndSpeciesSeldomWeight, SuitabilityLow(9) * CorcovPoorWeight, _
SuitabilityLow(10) * FishcountPoorWeight)

sumC = 0
For j = 1 To 4
   sumC = sumC + ProbC(j)
Next j

'Defuzzify Conservation
If sumC > 0 Then
   'calculation of suitability
   Call DefuzzCentroidC(ProbC(1), Centroid(1), ProbC(2), Centroid(2), _
   ProbC(3), Centroid(3), ProbC(4), Centroid(4), OutputValueC(1))
   'calculation of the upper limit
   Call DefuzzCentroidC(ProbC(1), UpperCentroid(1), ProbC(2), UpperCentroid(2), _
   ProbC(3), UpperCentroid(3), ProbC(4), UpperCentroid(4), OutputValueC(2))
   'calculation of the lower limit
   Call DefuzzCentroidC(ProbC(1), LowerCentroid(1), ProbC(2), LowerCentroid(2), _
   ProbC(3), LowerCentroid(3), ProbC(4), LowerCentroid(4), OutputValueC(3))
   'calculate increased suitability due to spawning
   Call SuitabilitySpawning2(SpawningDomain)

Worksheets("results").Cells(1 + i, 13).Value = Round(ProbC(4), 3)
Worksheets("results").Cells(1 + i, 14).Value = Round(ProbC(3), 3)
Worksheets("results").Cells(1 + i, 15).Value = Round(ProbC(2), 3)
Worksheets("results").Cells(1 + i, 16).Value = Round(ProbC(1), 3)
Worksheets("results").Cells(1 + i, 12).Value = Round(OutputValueC(1), 2)
Worksheets("results").Cells(1 + i, 17).Value = Round(OutputValueC(2), 2)
Worksheets("results").Cells(1 + i, 18).Value = Round(OutputValueC(3), 2)

End If

'Calculate PREF AND CONS
Prob(1) = MYCIN(SuitabilityLow(1) * DistVeryFarWeight, SuitabilityLow(2) * DepthVeryDeepWeight, _
SuitabilityLow(3) * RevLowWeight, SuitabilityLow(11) * AvgcatchLowWeight, SuitabilityLow(12) * BoatsManyWeight,
```

```
_ SuitabilityVeryHigh(9) * EndSpeciesOftenWeight, SuitabilityVeryHigh(14) * CorcovExcellentWeight, _
SuitabilityVeryHigh(15) * FishcountExcellentWeight, SuitabilityVeryHigh(16) * SeagrassWeight)

Prob(2) = MYCIN(SuitabilityModerate(1) * AvgcatchLowWeight, SuitabilityModerate(2) * DepthShallowWeight, _
SuitabilityModerate(3) * BoatsManyWeight, SuitabilityHigh(5) * EndSpeciesSometimesWeight, _
SuitabilityHigh(10) * CorcovGoodWeight, SuitabilityHigh(11) * FishcountGoodWeight, _
SuitabilityHigh(13) * SeagrassWeight, SuitabilityModerate(6) * RevHighDistVFarWeight, _
SuitabilityModerate(7) * AvgcatchModerateDistVFarWeight, SuitabilityModerate(8) * DistFarWeight)

Prob(3) = MYCIN(SuitabilityHigh(1) * AvgcatchModerateWeight, SuitabilityHigh(2) * DistFarWeight, _
SuitabilityHigh(3) * RevMediumWeight, SuitabilityHigh(4) * BoatsModerateWeight, _
SuitabilityHigh(12) * DepthDeepWeight, SuitabilityModerate(4) * CorcovFairWeight, SuitabilityModerate(5) *
FishcountFairWeight, _SuitabilityHigh(6) * RevVHighDistVFarWeight, SuitabilityHigh(7) *
AvgcatchHighDistVFarWeight, _SuitabilityModerate(9) * EndSpeciesSometimesWeight)

Prob(4) = MYCIN(SuitabilityVeryHigh(1) * AvgcatchHighWeight, SuitabilityVeryHigh(2) * DistVeryNearWeight, _
SuitabilityVeryHigh(3) * DepthDeepWeight, SuitabilityVeryHigh(4) * RevVeryHighWeight, _
SuitabilityVeryHigh(5) * BoatsFewWeight, SuitabilityVeryHigh(6) * DepthLittleDeepWeight, _
SuitabilityVeryHigh(7) * DistNearWeight, SuitabilityVeryHigh(8) * RevHighWeight, _
SuitabilityLow(4) * EndSpeciesSeldomWeight, SuitabilityLow(9) * CorcovPoorWeight, _
SuitabilityLow(10) * FishcountPoorWeight)

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'Calculate centroid, upper and lower centroids for defuzzification
‘~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Centroid(1) = FuzzCentroid(OutputFMFShape(1), SuitVeryHigh(1), SuitVeryHigh(2), SuitVeryHigh(3), SuitVeryHigh(4),
AlphaCutOutput(1))
Centroid(2) = FuzzCentroid(OutputFMFShape(2), SuitHigh(1), SuitHigh(2), SuitHigh(3), SuitHigh(4), AlphaCutOutput(2))
Centroid(3) = FuzzCentroid(OutputFMFShape(3), SuitModerate(1), SuitModerate(2), SuitModerate(3), SuitModerate(4),
AlphaCutOutput(3))
Centroid(4) = FuzzCentroid(OutputFMFShape(4), SuitLow(1), SuitLow(2), SuitLow(3), SuitLow(4), AlphaCutOutput(4))

'Upper centroid
UpperCentroid(1) = ConfLimit(ConfSuit, SuitVeryHigh(1), SuitVeryHigh(2), SuitVeryHigh(3), SuitVeryHigh(4), 1, 2)
UpperCentroid(2) = ConfLimit(ConfSuit, SuitHigh(1), SuitHigh(2), SuitHigh(3), SuitHigh(4), 1, 1)
UpperCentroid(3) = ConfLimit(ConfSuit, SuitModerate(1), SuitModerate(2), SuitModerate(3), SuitModerate(4), 1, 1)
UpperCentroid(4) = ConfLimit(ConfSuit, SuitLow(1), SuitLow(2), SuitLow(3), SuitLow(4), 1, 3)

'Lower centroid
LowerCentroid(1) = ConfLimit(ConfSuit, SuitVeryHigh(1), SuitVeryHigh(2), SuitVeryHigh(3), SuitVeryHigh(4), 0, 2)
LowerCentroid(2) = ConfLimit(ConfSuit, SuitHigh(1), SuitHigh(2), SuitHigh(3), SuitHigh(4), 0, 1)
LowerCentroid(3) = ConfLimit(ConfSuit, SuitModerate(1), SuitModerate(2), SuitModerate(3), SuitModerate(4), 0, 1)
LowerCentroid(4) = ConfLimit(ConfSuit, SuitLow(1), SuitLow(2), SuitLow(3), SuitLow(4), 0, 3)
```

```
        'Defuzzify Total
        sumPC = 0
        For j = 1 To 4
          sumPC = sumPC + Prob(j)
        Next j
        'Defuzify PREF and CONS
        If sumPC > 0 Then
          'calculation of suitability
          Call DefuzzCentroid(Prob(1), Centroid(1), Prob(2), Centroid(2), _
          Prob(3), Centroid(3), Prob(4), Centroid(4), OutputValue(1))
          'calculation of the upper limit
          Call DefuzzCentroid(Prob(1), UpperCentroid(1), Prob(2), UpperCentroid(2), _
          Prob(3), UpperCentroid(3), Prob(4), UpperCentroid(4), OutputValue(2))
          'calculation of the lower limit
          Call DefuzzCentroid(Prob(1), LowerCentroid(1), Prob(2), LowerCentroid(2), _
          Prob(3), LowerCentroid(3), Prob(4), LowerCentroid(4), OutputValue(3))
        'End If
        'Call WeightedOutput(OutputValueP(1), OutputValueC(1))
        Worksheets("results").Cells(1 + i, 29).Value = Round(Prob(4), 2)
        Worksheets("results").Cells(1 + i, 30).Value = Round(Prob(3), 2)
        Worksheets("results").Cells(1 + i, 31).Value = Round(Prob(2), 2)
        Worksheets("results").Cells(1 + i, 32).Value = Round(Prob(1), 2)
        Worksheets("results").Cells(1 + i, 33).Value = Round(OutputValue(2), 2)
        Worksheets("results").Cells(1 + i, 34).Value = Round(OutputValue(3), 2)
        Worksheets("results").Cells(1 + i, 28).Value = Round(OutputValue(1), 2)
       End If
'Calculate total suitability score based on user defined proportion of preference and conservation subcomponents
    Dim PrefWeight As Double
    Dim ConsWeight As Double
    Dim PrefScore As Double
    Dim ConsScore As Double
    PrefScore = Worksheets("results").Cells(1 + i, 2).Value
    ConsScore = Worksheets("results").Cells(1 + i, 12).Value
    PrefWeight = Worksheets("main").Cells(3, 2).Value
    ConsWeight = Worksheets("main").Cells(4, 2).Value
    WeightedOutputValue(1) = (OutputValueP(1) * PrefWeight + OutputValueC(1) * ConsWeight)
    Worksheets("results").Cells(1 + i, 20).Value = Round(WeightedOutputValue(1), 2)
'Calculate Weighted Probs
    Dim LowProbPref As Double
    Dim LowProbCons As Double
    Dim ModProbPref As Double
    Dim ModProbCons As Double
```

```
    Dim HighProbPref As Double
    Dim HighProbCons As Double
    Dim VHighProbPref As Double
    Dim VHighProbCons As Double
    LowProbPref = Worksheets("results").Cells(1 + i, 3).Value
    ModProbPref = Worksheets("results").Cells(1 + i, 4).Value
    HighProbPref = Worksheets("results").Cells(1 + i, 5).Value
    VHighProbPref = Worksheets("results").Cells(1 + i, 6).Value
    LowProbCons = Worksheets("results").Cells(1 + i, 13).Value
    ModProbCons = Worksheets("results").Cells(1 + i, 14).Value
    HighProbCons = Worksheets("results").Cells(1 + i, 15).Value
    VHighProbCons = Worksheets("results").Cells(1 + i, 16).Value
    WeightedOutputProb1(1) = (ProbP(4) * PrefWeight + ProbC(4) * ConsWeight)
    WeightedOutputProb2(1) = (ProbP(3) * PrefWeight + ProbC(3) * ConsWeight)
    WeightedOutputProb3(1) = (ProbP(2) * PrefWeight + ProbC(2) * ConsWeight)
    WeightedOutputProb4(1) = (ProbP(1) * PrefWeight + ProbC(1) * ConsWeight)
    Worksheets("results").Cells(1 + i, 21).Value = Round(WeightedOutputProb1(1), 2)
    Worksheets("results").Cells(1 + i, 22).Value = Round(WeightedOutputProb2(1), 2)
    Worksheets("results").Cells(1 + i, 23).Value = Round(WeightedOutputProb3(1), 2)
    Worksheets("results").Cells(1 + i, 24).Value = Round(WeightedOutputProb4(1), 2)
'Calculate Weighted Upper and Lower CL
    Dim UpperPref As Double
    Dim UpperCons As Double
    Dim LowerPref As Double
    Dim LowerCons As Double
    UpperPref = Worksheets("results").Cells(1 + i, 7).Value
    UpperCons = Worksheets("results").Cells(1 + i, 17).Value
    WeightedUpperValue(1) = (OutputValueP(2) * PrefWeight + OutputValueC(2) * ConsWeight)
    Worksheets("results").Cells(1 + i, 25).Value = Round(WeightedUpperValue(1), 2)
    LowerPref = Worksheets("results").Cells(1 + i, 8).Value
    LowerCons = Worksheets("results").Cells(1 + i, 18).Value
    WeightedLowerValue(1) = (OutputValueP(3) * PrefWeight + OutputValueC(3) * ConsWeight)
    Worksheets("results").Cells(1 + i, 26).Value = Round(WeightedLowerValue(1), 2)
End If
Next i
End Sub

'Calculate Weighted Upper and Lower CL
    Dim UpperPref As Double
    Dim UpperCons As Double
    Dim LowerPref As Double
    Dim LowerCons As Double
    UpperPref = Worksheets("results").Cells(1 + i, 7).Value
```

```
    UpperCons = Worksheets("results").Cells(1 + i, 17).Value
    WeightedUpperValue(1) = (OutputValueP(2) * PrefWeight + OutputValueC(2) * ConsWeight)
    Worksheets("results").Cells(1 + i, 25).Value = Round(WeightedUpperValue(1), 2)
    LowerPref = Worksheets("results").Cells(1 + i, 8).Value
    LowerCons = Worksheets("results").Cells(1 + i, 18).Value
    WeightedLowerValue(1) = (OutputValueP(3) * PrefWeight + OutputValueC(3) * ConsWeight)
    Worksheets("results").Cells(1 + i, 26).Value = Round(WeightedLowerValue(1), 2)

'Calculate midpoint for preference subcomponent
Sub DefuzzCentroidP(OutputMemberP1 As Double, CentroidP1 As Double, OutputMemberP2 As Double, CentroidP2 As
Double, _OutputMemberP3 As Double, CentroidP3 As Double, OutputMemberP4 As Double, CentroidP4 As Double, ByRef
OutputValueP As Double)
        OutputValueP = (OutputMemberP1 * CentroidP1 + OutputMemberP2 * CentroidP2 + OutputMemberP3 * CentroidP3 _
        + OutputMemberP4 * CentroidP4) / (OutputMemberP1 + OutputMemberP2 + OutputMemberP3 + OutputMemberP4)
End Sub

'Calculate midpoint for conservation subcomponent
Sub DefuzzCentroidC(OutputMemberC1 As Double, CentroidC1 As Double, OutputMemberC2 As Double, CentroidC2 As
Double, _OutputMemberC3 As Double, CentroidC3 As Double, OutputMemberC4 As Double, CentroidC4 As Double, ByRef
OutputValueC As Double)
        OutputValueC = (OutputMemberC1 * CentroidC1 + OutputMemberC2 * CentroidC2 + OutputMemberC3 * CentroidC3 _
        + OutputMemberC4 * CentroidC4) / (OutputMemberC1 + OutputMemberC2 + OutputMemberC3 + OutputMemberC4)
End Sub

'Calculate midpoint for total suitability score
Sub DefuzzCentroid(OutputMember1 As Double, Centroid1 As Double, OutputMember2 As Double, Centroid2 As Double, _
OutputMember3 As Double, Centroid3 As Double, OutputMember4 As Double, Centroid4 As Double, ByRef OutputValue As
Double)
        OutputValue = (OutputMember1 * Centroid1 + OutputMember2 * Centroid2 + OutputMember3 * Centroid3 _
        + OutputMember4 * Centroid4) / (OutputMember1 + OutputMember2 + OutputMember3 + OutputMember4)
End Sub

'Increase score if there is spawning fish
Sub SuitabilitySpawning2(SpawningDomain As Double)
    Dim OutputValueSpawn As Double
    Dim OutputValueSpawn2 As Double
    Dim OutputValueSpawnUp As Double
    Dim OutputValueSpawnLow As Double
    OutputValueSpawn = 0
    OutputValueSpawn2 = 0
    OutputValueSpawnUp = 0
    OutputValueSpawnLow = 0
        OutputValueSpawn = OutputValueC(1) * (1 + SuitabilitySpawn)
```

```
    OutputValueSpawnUp = OutputValueC(2) * (1 + SuitabilitySpawn)
    OutputValueSpawnLow = OutputValueC(3) * (1 + SuitabilitySpawn)
    OutputValueSpawn2 = OutputValue(1) * (1 + SuitabilitySpawn)
    If SpawningDomain > 0 Then
      OutputValueC(1) = OutputValueSpawn
      OutputValueC(2) = OutputValueSpawnUp
      OutputValueC(3) = OutputValueSpawnLow
      OutputValue(1) = OutputValueSpawn2
      OutputValueC(2) = OutputValueC(1)
        If OutputValueC(1) > 10 Then OutputValueC(1) = 10
        If OutputValueC(2) > 10 Then OutputValueC(2) = 10
        If OutputValue(1) > 10 Then OutputValue(1) = 10
   End If
End Sub
Function MYCIN(Evidence1 As Double, Evidence2 As Double, Optional Evidence3 As Double, Optional Evidence4 As Double,
_Optional Evidence5 As Double, Optional Evidence6 As Double, Optional Evidence7 As Double, Optional Evidence8 As
Double, _Optional Evidence9 As Double, Optional Evidence10 As Double, Optional Evidence11 As Double, Optional
Evidence12 As Double, _Optional Evidence13 As Double, Optional Evidence14 As Double, Optional Evidence15 As Double,
Optional Evidence16 As Double)

    '~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    'MYCIN function for accumulating evidence
    '~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    Dim clue As Double
    clue = 0
    clue = Evidence1
    clue = clue + Evidence2 * (1 - clue)
    clue = clue + Evidence3 * (1 - clue)
    clue = clue + Evidence4 * (1 - clue)
    clue = clue + Evidence5 * (1 - clue)
    clue = clue + Evidence6 * (1 - clue)
    clue = clue + Evidence7 * (1 - clue)
    clue = clue + Evidence8 * (1 - clue)
    clue = clue + Evidence9 * (1 - clue)
    clue = clue + Evidence10 * (1 - clue)
    clue = clue + Evidence11 * (1 - clue)
    clue = clue + Evidence12 * (1 - clue)
    clue = clue + Evidence13 * (1 - clue)
    clue = clue + Evidence14 * (1 - clue)
    clue = clue + Evidence15 * (1 - clue)
    clue = clue + Evidence16 * (1 - clue)
    MYCIN = clue
End Function
```

```
Function ConfLimit(ConfSuit As Double, a As Double, b As Double, c As Double, d As Double, UpperLower As Integer,
FMFShape As Integer) As Double
    'Upperlower, 0=lower, 1=upper
    Dim temp1 As Double, temp2 As Double
    If FMFShape = 1 Then
        temp1 = c - ConfSuit * (c - b)
        temp2 = a + ConfSuit * (b - a)
        If UpperLower = 0 Then ConfLimit = WorksheetFunction.Min(temp1, temp2)
        If UpperLower = 1 Then ConfLimit = WorksheetFunction.Max(temp1, temp2)
    Else
        If FMFShape = 2 Then
            temp2 = d - ConfSuit * (d - c)
            If UpperLower = 0 Then ConfLimit = a
            If UpperLower = 1 Then ConfLimit = temp2
        Else
            temp1 = a + ConfSuit * (b - a)
            If UpperLower = 0 Then ConfLimit = temp1
            If UpperLower = 1 Then ConfLimit = d
        End If
    End If
End Function

Sub ReadInputFMF(StartRow As Integer, StartColumn As Integer, VariableNo As Integer, ByRef Domain() As Double,
alphacut() As Double, FMFShape() As Integer)
    Dim i As Integer, j As Integer
    For i = 1 To VariableNo
        For j = 1 To 4
            Domain(i, j) = Worksheets("FMF").Cells(StartRow + i, StartColumn + 1 + j).Value
        Next j
        alphacut(i) = Worksheets("FMF").Cells(StartRow + i, 7).Value
        FMFShape(i) = Worksheets("FMF").Cells(StartRow + i, 2).Value
    Next i
 End Sub
Option Explicit
Sub HeuristicAvgcatchLow(antecedent As Double, Optional alphacut As Double)
    'Rule: If catch is low Then preference is moderate
    If antecedent >= alphacut Then
    If antecedent > SuitabilityModerate(1) Then
        SuitabilityModerate(1) = antecedent
    End If
    End If
End Sub
```

```
Sub HeuristicAvgcatchLow2(antecedent As Double, Optional alphacut As Double)
    'Rule: If catch is low Then preference is low
    If antecedent >= alphacut Then
    If antecedent > SuitabilityLow(11) Then
        SuitabilityLow(11) = antecedent
    End If
    End If
End Sub
Sub HeuristicAvgcatchModerate(antecedent As Double, Optional alphacut As Double)
    'Rule: If catch is moderate Then preference is high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityHigh(1) Then
        SuitabilityHigh(1) = antecedent
    End If
    End If
End Sub
Sub HeuristicAvgcatchModerateDistVFar(Antecedent1 As Double, Antecedent2 As Double, Optional alphacut As Double)
    'Rule: If Catch is moderate AND Distance is very far Then Preference is Moderate
    Dim antecedent As Double
    antecedent = 0
    If Antecedent1 <> 0 Then
    antecedent = Antecedent1
        If antecedent > alphacut Then
            If antecedent > SuitabilityHigh(1) Then
                SuitabilityHigh(1) = antecedent 'MYCIN will be SuitabilityHigh(1)*AvgcatchModerateWeight
                    If Antecedent2 <> 0 Then
                        antecedent = 0
                        antecedent = Antecedent1
                            If antecedent > Antecedent2 Then antecedent = Antecedent2
                                If antecedent > SuitabilityModerate(7) Then
                                    SuitabilityModerate(7) = antecedent 'MYCIN will be
SuitabilityModerate(7)*AvgcatchModerateDistVFarWeight
                                End If
                            End If
                    End If
            End If
        End If
End Sub
Sub HeuristicAvgcatchHigh(antecedent As Double, Optional alphacut As Double)
    'Rule: If catch is high Then preference is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(1) Then
        SuitabilityVeryHigh(1) = antecedent
```

```
    End If
    End If
End Sub
Sub HeuristicAvgcatchHighDistVFar(Antecedent1 As Double, Antecedent2 As Double, Optional alphacut As Double)
    'Rule: If Catch is high AND Distance is very far Then Preference is High
    Dim antecedent As Double
    antecedent = 0
    If Antecedent1 <> 0 Then
    antecedent = Antecedent1
        If antecedent > alphacut Then
            If antecedent > SuitabilityVeryHigh(1) Then
                SuitabilityVeryHigh(1) = antecedent 'MYCIN will be SuitabilityVeryHigh(1)*AvgcatchHighWeight
                    If Antecedent2 <> 0 Then
                        antecedent = 0
                        antecedent = Antecedent1
                            If antecedent > Antecedent2 Then antecedent = Antecedent2
                                If antecedent > SuitabilityHigh(7) Then
                                    SuitabilityHigh(7) = antecedent 'MYCIN will be SuitabilityHigh(7)*AvgcatchHighDistVFarWeight
                                End If
                            End If
                    End If
            End If
        End If
End Sub
Sub HeuristicDistVeryFar(antecedent As Double, Optional alphacut As Double)
    'Rule: If distance to closest village is very far Then preference is low
    If antecedent >= alphacut Then
    If antecedent > SuitabilityLow(1) Then
        SuitabilityLow(1) = antecedent
    End If
    End If
End Sub
Sub HeuristicDistFar(antecedent As Double, Optional alphacut As Double)
    'Rule: If distance is far Then preference is high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityHigh(2) Then
        SuitabilityHigh(2) = antecedent
    End If
    End If
End Sub
Sub HeuristicDistFar2(antecedent As Double, Optional alphacut As Double)
    'Rule: If distance is far Then preference is moderate
    If antecedent >= alphacut Then
```

```
    If antecedent > SuitabilityModerate(8) Then
      SuitabilityModerate(8) = antecedent
    End If
    End If
End Sub
Sub HeuristicDistNear(antecedent As Double, Optional alphacut As Double)
    'Rule: If distance is near Then preference is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(2) Then
      SuitabilityVeryHigh(2) = antecedent
    End If
    End If
End Sub
Sub HeuristicDistVeryNear(antecedent As Double, Optional alphacut As Double)
    'Rule: If distance is very near Then preference is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(3) Then
      SuitabilityVeryHigh(3) = antecedent
    End If
    End If
End Sub
Sub HeuristicDepthVeryDeep(antecedent As Double, Optional alphacut As Double)
    'Rule: If depth is very deep Then preference is low
    If antecedent >= alphacut Then
    If antecedent > SuitabilityLow(2) Then
      SuitabilityLow(2) = antecedent
    End If
    End If
End Sub
Sub HeuristicDepthDeep(antecedent As Double, Optional alphacut As Double)
    'Rule: If depth is deep Then preference is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(4) Then
      SuitabilityVeryHigh(4) = antecedent
    End If
    End If
End Sub
Sub HeuristicDepthDeep2(antecedent As Double, Optional alphacut As Double)
    'Rule: If depth is deep Then preference is high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityHigh(12) Then
      SuitabilityHigh(12) = antecedent
    End If
```

```
    End If
End Sub
Sub HeuristicDepthLittleDeep(antecedent As Double, Optional alphacut As Double)
    'Rule: If depth is a little deep Then preference is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(5) Then
        SuitabilityVeryHigh(5) = antecedent
    End If
    End If
End Sub
Sub HeuristicDepthShallow(antecedent As Double, Optional alphacut As Double)
    'Rule: If depth is a shallow Then preference is moderate
    If antecedent >= alphacut Then
    If antecedent > SuitabilityModerate(2) Then
        SuitabilityModerate(2) = antecedent
    End If
    End If
End Sub
Sub HeuristicRevLow(antecedent As Double, Optional alphacut As Double)
    'Rule: If revenue is a low Then preference is low
    If antecedent >= alphacut Then
    If antecedent > SuitabilityLow(3) Then
        SuitabilityLow(3) = antecedent
    End If
    End If
End Sub
Sub HeuristicRevMedium(antecedent As Double, Optional alphacut As Double)
    'Rule: If Rev is medium Then preference is high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityHigh(3) Then
        SuitabilityHigh(3) = antecedent
    End If
    End If
End Sub
Sub HeuristicRevHigh(antecedent As Double, Optional alphacut As Double)
    'Rule: If depth is a little deep Then preference is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(6) Then
        SuitabilityVeryHigh(6) = antecedent
    End If
    End If
End Sub
Sub HeuristicRevHighDistVFar(Antecedent1 As Double, Antecedent2 As Double, Optional alphacut As Double)
```

```
    'Rule: If revenue is high AND Distance is very far Then Preference is Moderate
    Dim antecedent As Double
    antecedent = 0
    If Antecedent1 <> 0 Then
    antecedent = Antecedent1
      If antecedent > alphacut Then
        If antecedent > SuitabilityVeryHigh(6) Then
          SuitabilityVeryHigh(6) = antecedent 'MYCIN will be SuitabilityVeryHigh(6)*RevHighWeight
            If Antecedent2 <> 0 Then
              antecedent = 0
              antecedent = Antecedent1
                If antecedent > Antecedent2 Then antecedent = Antecedent2
                  If antecedent > SuitabilityModerate(6) Then
                    SuitabilityModerate(6) = antecedent 'MYCIN will be SuitabilityModerate(6)*RevHighDistVFarWeight
                  End If
                End If
            End If
        End If
      End If
End Sub
Sub HeuristicRevVeryHigh(antecedent As Double, Optional alphacut As Double)
    'Rule: If depth is a little deep Then preference is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(7) Then
      SuitabilityVeryHigh(7) = antecedent
    End If
    End If
End Sub
Sub HeuristicRevVHighDistVFar(Antecedent1 As Double, Antecedent2 As Double, Optional alphacut As Double)
    'Rule: If Revenue is very high AND Distance is very far Then preference is High
    Dim antecedent As Double
    antecedent = 0
    If Antecedent1 <> 0 Then
    antecedent = Antecedent1
      If antecedent > alphacut Then
        If antecedent > SuitabilityVeryHigh(7) Then
          SuitabilityVeryHigh(7) = antecedent 'MYCIN will be SuitabilityVeryHigh(7)*RevVeryHighWeight
            If Antecedent2 <> 0 Then
              antecedent = 0
              antecedent = Antecedent1
                If antecedent > Antecedent2 Then antecedent = Antecedent2
                  If antecedent > SuitabilityHigh(6) Then
                    SuitabilityHigh(6) = antecedent 'MYCIN will be SuitabilityHigh(6)*RevVHighDistVFarWeight
```

```
                End If
              End If
          End If
      End If
    End If
End Sub

Sub HeuristicBoatsFew(antecedent As Double, Optional alphacut As Double)
  'Rule: If number of boats is few Then preference is very high
  If antecedent >= alphacut Then
  If antecedent > SuitabilityVeryHigh(8) Then
    SuitabilityVeryHigh(8) = antecedent
  End If
  End If
End Sub
Sub HeuristicBoatsModerate(antecedent As Double, Optional alphacut As Double)
  'Rule: If number of boats is moderate Then preference is high
  If antecedent >= alphacut Then
  If antecedent > SuitabilityHigh(4) Then
    SuitabilityHigh(4) = antecedent
  End If
  End If
End Sub
Sub HeuristicBoatsMany(antecedent As Double, Optional alphacut As Double)
  'Rule: If number of boats is many Then preference is moderate
  If antecedent >= alphacut Then
  If antecedent > SuitabilityModerate(3) Then
    SuitabilityModerate(3) = antecedent
  End If
  End If
End Sub
Sub HeuristicBoatsMany2(antecedent As Double, Optional alphacut As Double)
  'Rule If number of boats is many Then preference is low and suitability is very high
  If antecedent >= alphacut Then
  If antecedent > SuitabilityLow(12) Then
    SuitabilityLow(12) = antecedent
  End If
  End If
End Sub
Sub HeuristicEndSpeciesSeldom(antecedent As Double, Optional alphacut As Double)
  'Rule: If Sighting of turtle is seldom Then suitability is low
  If antecedent >= alphacut Then
  If antecedent > SuitabilityLow(4) Then
```

```
      SuitabilityLow(4) = antecedent
    End If
    End If
End Sub
Sub HeuristicEndSpeciesSometimes(antecedent As Double, Optional alphacut As Double)
    'Rule: If Sighting of turtle is sometimes Then suitability is high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityHigh(5) Then
      SuitabilityHigh(5) = antecedent
    End If
    End If
End Sub
Sub HeuristicEndSpeciesSometimes2(antecedent As Double, Optional alphacut As Double)
    'Rule: If Sighting of turtle is sometimes Then suitability is high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityModerate(9) Then
      SuitabilityModerate(9) = antecedent
    End If
    End If
End Sub
Sub HeuristicEndSpeciesOften(antecedent As Double, Optional alphacut As Double)
    'Rule: If Sighting of turtle is often Then suitability is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(9) Then
      SuitabilityVeryHigh(9) = antecedent
    End If
    End If
End Sub

Sub HeuristicCorcovPoor(antecedent As Double, Optional alphacut As Double)
    'Rule: If coralcover is poor Then suitability is low
    If antecedent >= alphacut Then
    If antecedent > SuitabilityLow(9) Then
      SuitabilityLow(9) = antecedent
    End If
    End If
End Sub
Sub HeuristicCorcovFair(antecedent As Double, Optional alphacut As Double)
    'Rule: If coralcover is fair Then suitability is moderate
    If antecedent >= alphacut Then
    If antecedent > SuitabilityModerate(4) Then
      SuitabilityModerate(4) = antecedent
    End If
```

```
    End If
End Sub
Sub HeuristicCorcovGood(antecedent As Double, Optional alphacut As Double)
    'Rule: If coralcover is good Then suitability is high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityHigh(10) Then
        SuitabilityHigh(10) = antecedent
    End If
    End If
End Sub
Sub HeuristicCorcovExcellent(antecedent As Double, Optional alphacut As Double)
    'Rule: If coralcover is excellent Then suitability is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(14) Then
        SuitabilityVeryHigh(14) = antecedent
    End If
    End If
End Sub
Sub HeuristicFishcountPoor(antecedent As Double, Optional alphacut As Double)
    'Rule: If fish count is poor Then suitability is low
    If antecedent >= alphacut Then
    If antecedent > SuitabilityLow(10) Then
        SuitabilityLow(10) = antecedent
    End If
    End If
End Sub
Sub HeuristicFishcountFair(antecedent As Double, Optional alphacut As Double)
    'Rule: If fish count is fair Then suitability is moderate
    If antecedent >= alphacut Then
    If antecedent > SuitabilityModerate(5) Then
        SuitabilityModerate(5) = antecedent
    End If
    End If
End Sub
Sub HeuristicFishcountGood(antecedent As Double, Optional alphacut As Double)
    'Rule: If fish count is good Then suitability is high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityHigh(11) Then
        SuitabilityHigh(11) = antecedent
    End If
    End If
End Sub
Sub HeuristicFishcountExcellent(antecedent As Double, Optional alphacut As Double)
```

```
    'Rule: If Fishcount is excellent Then suitability is very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(15) Then
        SuitabilityVeryHigh(15) = antecedent
    End If
    End If
End Sub
Sub HeuristicSeagrass(antecedent As Double, Optional alphacut As Double)
'Rule: If seagrass is present Then Suitability is high and very high
    If antecedent >= alphacut Then
    If antecedent > SuitabilityVeryHigh(16) Then
    If antecedent > SuitabilityHigh(13) Then
        SuitabilityVeryHigh(16) = antecedent
        'SuitabilityHigh(13) = antecedent
    End If
    End If
    End If
End Sub
Sub HeuristicSpawn2(antecedent As Double, Optional alphacut As Double)
' Rule: If spawning is present Then Suitability Score increases by the value of SuitabilitySpawn
    If antecedent > alphacut Then
    If antecedent > SuitabilitySpawn Then
        SuitabilitySpawn = antecedent
    End If
    End If
End Sub

'## Membership Functions from WWL Cheung##
Function Triangle(x As Double, a As Double, b As Double, c As Double) As Double
Dim temp As Double
    If x <= a Then temp = 0
    If x > a And x < b Then temp = (x - a) / (b - a)
    If x >= b And x < c Then temp = (c - x) / (c - b)
    If x >= c Then temp = 0
    Triangle = temp
End Function
Function trapezoid(x As Double, a As Double, b As Double, c As Double, d As Double) As Double
Dim temp As Double

    If x <= a Then temp = 0
    If x > a And x < b Then temp = (x - a) / (b - a)
    If x >= b And x < c Then temp = 1
    If x >= c And x < d Then temp = (d - x) / (d - c)
```

```
    If x >= d Then temp = 0
    trapezoid = temp
End Function
Public Function Logistic_G(x As Double, alpha As Double, beta As Double, gamma As Double)
' return a S-curve FMF with growing degree of membership
' Alpha - Domain with zero membership
' Beta - Inflection point
' Gamma - Domain with full membership
    If x <= alpha Then Logistic_G = 0
    If x >= alpha And x <= beta Then Logistic_G = 2 * ((x - alpha) / (gamma - alpha)) ^ 2
    If x >= beta And x <= gamma Then Logistic_G = 1 - 2 * ((x - gamma) / (gamma - alpha)) ^ 2
    If x >= gamma Then Logistic_G = 1
 End Function
Public Function Logistic_D(x As Double, alpha As Double, beta As Double, gamma As Double)
' return a S-curve FMF with declining degree of membership
' Alpha - Domain with zero membership
' Beta - Inflection point
' Gamma - Domain with full membership
    If x <= alpha Then Logistic_D = 0
    If x >= alpha And x <= beta Then Logistic_D = 2 * ((x - alpha) / (gamma - alpha)) ^ 2
    If x >= beta And x <= gamma Then Logistic_D = 1 - 2 * ((x - gamma) / (gamma - alpha)) ^ 2
    If x >= gamma Then Logistic_D = 1
    Logistic_D = 1 - Logistic_D
End Function
```