Agent-based model on the effects of dive tourism in coral related social-ecological system

A case study on Koh Tao, Thailand

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ABBREVIATIONS

ABM	Agent Based Modeling
AMNP	Angthong Marine National Park (Thailand)
DMCR	Department of Marine and Coastal Resource Thailand
EMP	Ecological Monitoring Programs on Koh Tao
MNPD	Marine National Park Division Thailand
PADI	Professional Association of Diving Instructors
SD	Standard Division
SE	Standard Error
SES	Social-Ecological System
SSI	Scuba Schools International
TAT	Tourism Authority of Thailand

ABSTRACT

Alongside the impacts of global environment change, dive tourism represents an important influence on coral reefs on a regional scale. The degradation of coral reefs, especially at dive tourism destinations, is known to have occurred worldwide as a result of interrelated socio-economic and ecological change processes. Thus it is appropriate to consider and analyse coral reefs and the societies that interact with them as social-ecological systems (SES), rather considering social and/or ecological aspects separately. Although a growing number of transdisciplinary approaches have been developed for the study of these complex systems, analysis of their dynamical interactions remains a challenging undertaking.

This study uses an agent-based model (ABM), called KohTaoSim, to represent the complex dynamics of a dive-tourism related SES, using the island of Koh Tao, Thailand as a case study. The dissertation describes the participatory and iterative modelling process: empirical social data collection was followed by the transformation of social science knowledge and local ecological knowledge into ABM algorithms and model parameterization. Initial results were subjected to an iterative validation process with the assistance and input from Thai government officials, local coral ecologists and local community members. This ensured that KohTaoSim adequately captured the basic behavior and dynamics of the SES, including feedback processes between natural (coral reefs) and social (tourists, dive school and other institutions) system components. The model simulates community decision-making processes and the aggregated dynamics of coral reefs, thereby providing insights into the drivers of change in this complex, self-organizing system. KohTaoSim enables analysing the effects of dive tourism on coral reefs, in conjunction with other local and global threats, and evaluating the effectiveness of different management measures in contributing towards system sustainability.

The results of testing KohTaoSim under different environmental and management scenarios indicate that, from an ecological perspective, large scale environmental disturbances, especially mass mortality events (e.g. bleaching) play a dominant role in coral degradation. Local stressors will however compound and exacerbate the effects of global stressors. Among these, terrestrial sources of marine pollution, caused in part by rapid tourism development (e.g. sewage outflows, sedimentation) are much more influential than direct damage to corals by SCUBA divers and snorkelers. From a social-economic perspective, visitor numbers are the most important factor affecting the incomes of dive schools; results suggest that these are to a large extent self-regulating. Large-scale damage to corals under a worst case environmental scenario will not greatly reduce visitor numbers or dive school incomes but will lead to a reduction in the use of vulnerable nearshore sites and, over time, the disappearance of snorkeling as a recreational activity on Koh Tao. From a management perspective, the construction of artificial dive sites may have the potential to reduce the dive pressure at natural dive sites, as well as increasing the overall income of the Koh Tao dive tourism industry. Neither eco-labeling of dive schools, often considered as a marketing tool to promote pro-environmental dive tourism businesses, nor environmental education programs can be expected to lead to a marked improvement of coral health. However, an increase of the overall incomes of dive schools can be expected, as visitors will be more prepared to pay the higher prices charged by eco-dive schools. However waste water treatment and reforestation are the management actions that will bring most benefits, both from an ecological and an economic perspective.

Agent-based modelling was found to be an appropriate option for analysis of this coral-based dive tourism SES. Firstly, it enabled the spatial and temporal dynamics of the system to be captured and analyzed. Second it enabled empirical data from social research to be integrated into the model, to show the effects of social dynamics on ecological processes and vice versa. Thirdly, the freedom to define agents of different types and acting at different scales facilitated cross-disciplinary and cross-scale analysis. Finally, and most importantly, the ABM allowed local stakeholders to become fully involved in the iterative modeling procedure, and provided a platform for them to formulate their own management proposals.

KohTaoSim, together with its adjustable user interface, is intended to be an open source software application that can be used as a tool for environmental education and management. Management strategies recommended and evaluated in this study will provide inputs to decision-making aimed at ensuring sustainable tourism development on Koh Tao.

ZUSAMMENFASSUNG

Neben der globalen Umweltveränderung ist der Tauchtourismus ein wichtiger lokaler Einflussfaktor für Korallenriffe. Die Degradation von Korallenriffen, insbesondere an Tauchtourismuszielen, erfolgt als eine Folge des verknüpften sozioökonomischen und ökologischen Wandels. Daher ist es sinnvoll, Korallenriffe und die mit ihnen verbundenen sozialen Systeme als interagierendes sozial-ökologisches System (SES) zu betrachten und zu analysieren. Obwohl es eine große Anzahl von transdisziplinären Studien zur der Erklärung dieses komplexen Systems gibt, bleibt die Analyse ihrer Dynamik eine Herausforderung.

Die vorliegende Studie verwendet ein Agentenbasiertes Model (ABM, hier KohTaoSim genannt), um die komplexe Dynamik des Tauchtourismus am Beispiel der Insel Koh Tao, Thailand, darzustellen. Diese Dissertation verfolgt einen partizipativen und iterativen Modellierungsprozess: die sozioökonomischen Daten aus der empirischen Erhebung wurden zur Entwicklung von Algorithmen und zur Parameterisierung des ABMs genutzt. Die daraus resultierenden Ergebnisse wurden einem in einem iterativen Validatierungsprozess, unter Beteiligung von Regierungsbeamten, lokalen Ökologen und Mitgliedern der lokalen Bevölkerung, genutzt, um das Model zu verbessern. Hierdurch wurde sichergestellt, dass KoTaoSim das grundlegende Verhalten und die Dynamiken des SES korrekt darstellt, unter Einbeziehung der Rückkopplungsprozesse zwischen natürlichen und gesellschaftlichen Prozessen. Das entstandene Modell simuliert sowohl die Entscheidungsprozesse der Gemeinschaft und die Dynamik der Korallenriffe, um auf diese Weise die treibenden Faktoren dieses komplexen, sich selbst organisierenden Systems zu untersuchen und in Verbindung mit anderen lokalen und globalen Gefahren, die Effizienz von verschiedenen Managementstrategien in Bezug auf die Nachhaltigkeit des Systems zu evaluieren.

Die unter verschiedenen Ökologischen- und Managementszenarien getesteten Resultate zeigen, dass großräumige Umwelteinflüsse, insbesondere Massensterben der Korallen (z.B. durch Bleichen), eine dominante Rolle bei der Korallenriffdegradation spielen. Lokale Stressoren verschärfen die Auswirkungen der globalen Stressoren. Unter diesen Faktoren sind die partiell durch den rapide wachsenden Tourismus verursachten marinen Verschmutzungen terrestrischen Ursprungs (z.B. Abwasser und Sedimentation) schwerwiegender als der direkte Einfluss/Schaden durch Taucher und Schnorchler. Aus ökonomischer Perspektive ist die Anzahl der Besucher die wichtigste Einkommensquelle für die Tauchschulen. Die Resultate des Modells ergeben, dass es sich hier weitgehend um einen selbstregulierenden Prozess handelt. Des Weiteren zeigt die Analyse, dass selbst wenn umweltbelastende Worst-Case-Szenarien (z.B. großflächige Beschädigungen) angenommen werden, die Besucherzahlen und Einkommen der Tauchschulen nicht im großen Maßstab beeinträchtigt werden, jedoch die Umweltbelastung zu einer Reduzierung von küstennahen Tauchplätzen (Riffen) führt. Langfristig könnte diese Entwicklung auch dazu führen, dass das Schnorcheln als Freizeitbeschäftigung auf Koh Tao verschwindet. Aus der Managementperspektive würde die Errichtung künstlicher Tauchattraktion den Druck (an Tauchern) von den natürlichen Korallenriffen nehmen, zudem würde laut KohTaoSim eine Erhöhung des Einkommens für die Tauchtourismusindustrie möglich werden. Auf der anderen Seite zeigen die Ergebnisse, dass weder die häufig als Marketingstrategie eingesetzte Implementierung von Ökolabels für Tauchschulen, noch die Einrichtung von Schulungen der Touristen und lokalen Bevölkerung im ökologischen Bewusstsein zu einer entscheidenden Verbesserung des Zustandes der Korallenriffe führen. Eine Verbesserung des Einkommens der Tauchschulen ist allerdings festzustellen, da die Touristen bereit sind, für die ökologischen Standards der Tauschulen mehr auszugeben. Aus ökologischer und ökonomischer Perspektive sind die Einführung von

Abwassersystemen und Aufforstung die effektivsten Mittel.

Die vorliegende Arbeit zeigt, dass ein Agentenbasiertes Modell ein gutes Instrument ist, um die Einflüsse des Tauchtourismus auf das SES zu analysieren. Erstens ermöglicht der Modellansatz die räumlichen und zeitlichen Systemdynamiken zu erfassen. Zweitens konnten die aus der sozialwissenschaftlichen Forschung resultierenden empirischen Daten in das Modell integriert werden, um den Zusammenhang zwischen den sozialen und den ökologischen Faktoren effektiver zu begreifen. Drittens bietet das ABM die Möglichkeit, auf mehreren Ebenen unterschiedlich agierende Agenten zu definieren. Dies unterstützte die interdisziplinäre Analyse entscheidend. Schließlich, als ganz wesentliches Kriterium, führte das ABM dazu, dass lokale Interessengruppen auf den Prozess der Modellierung Einfluss nehmen konnten, wodurch eine Plattform zur Verfügung gestellt werden konnte, mit der eigene Managementvorschläge in Hinblick auf ihre Auswirkungen getestet werden können.

KohTao Sim ist als Open Source Software Anwendung ausgelegt, die eine anpassungsfähige Benutzeroberflasche anbietet und als effektives Instrument zur Umwelterziehung und zum Management eingesetzt werden kann. Die Managementstrategien, die in dieser Studie untersucht wurden, bieten die Möglichkeit Entscheidungsprozesse in Bezug auf die Entwicklung einer nachhaltigen Tourismusindustrie in Koh Tao positiv zu beeinflussen.

Chapter I: INTRODUCTION

1.1 Reefs

Coral reefs are among the most biodiverse ecosystems on the planet. A wide array of organisms finds niches in their complex three-dimensional structures. Such structural complexity is partially responsible for the high biodiversity and productivity of coral reef ecosystems. Serving as an important asset for coastal human communities, reefs are a source of food as well as a bank of genetic resources, and offer protection to coastal cities and settlements from storms. They are also tourist attractions. As a major location for marine-based economic and recreational activities, such as coral-based dive tourism and the associated residential/commercial development, coral reefs make a significant contribution to the economies of many countries and regions, e.g. Egypt (Gladstone et al. 2013), Mexico (Wilson 2008), Honduras (Doiron and Weissenberger 2014), the Philippines (Fabinyi 2008), Portugal (Rangel et al. 2014), Australia (Biggs 2011), and Pacific Islands countries (Narayan et al. 2010). Coral reefs are particularly important for small island states. Taking the Maldives as an example, studies show a trend of rapidly growing tourism, which is largely dependent on the attraction of the surrounding coral reefs in the Indian Ocean and currently accounts directly for one-third of the GDP, a proportion that rises to between 60 and 70% if indirect impacts are considered (Cater 2010).

However, coral reefs around the world now face considerable threats and the rate of coastal reef decline is alarming (Burke et al. 2011). It is estimated that about 10% of all coral reefs are degraded beyond recovery, while about 30% are in a critical condition and may die in the next decades (Bellwood et al. 2004). For example, in Southeast Asia up to 40% of reef areas had already been effectively destroyed by 2008 (Doshi et al. 2012). This is the region facing the severest threats, with 80% of reefs classified as being at high or medium risk (Asafu-Adjaye and Tapsuwan 2008). Changes in global factors, e.g. ocean acidification and climate change (Smith and Buddemeier 1992, Hoegh-Guldberg et al. 2007), have effects that are responsible for a large proportion of coral losses. But on a regional scale, overfishing (Jackson et al. 2001), watershed pollution (Fabricius 2005, Liu et al. 2012) and unsustainable tourism development (Zakai and Chadwickfurman 2002, Juhasz et al. 2010) also cause extensive, cumulative damage, and should not be ignored.

1.2 Dive tourism

People in many parts of the world are dependent on coral reefs and make a living from direct extraction and/or use of their resources, for example through fishing and recreational activities such as dive tourism (Prayaga et al. 2010). Dive tourism in marine and coastal areas, particularly SCUBA diving and snorkelling, has increased considerably in recent years. From a niche market based on a specialized interest in marine environments, it has become a mass tourism activity (Gössling 2001). Dive tourism is now a global business with an annual growth rate of around 6%, and employing approximately 900,000 newly certified SCUBA divers each year (PADI 2016).

This is a two-sided coin. On one hand, such rapid development of dive tourism can put pressure on coral reefs beyond the capacity of current management regimes, especially in tropical countries (De Groot and Bush 2010) as there are few incentives for tourists and dive operators to act in ways that are compatible with the sustainability of marine ecosystems, and coral reefs in particular. Consequently, in addition to impacts of global threats, the decline in the health of coral reefs has been shown to be linked to rapid growth of dive tourism on a regional scale (Cesar and Beukering 2004, Cater 2010). Studies show that a dramatic increase in sedimentation (Rogers 1990) and sewage disposal (Liu et al. 2012) during tourism development, and physical breakage (Hasler and Ott 2008) during diving activities, can all have a serious impact on coral reefs. The severity of this impact depends on the extent to which measures are taken to reduce sedimentation, the efficiency of sewage treatment, and the dive density and behaviour of divers at a specific location (Tratalos and Austin 2001, Barker and Roberts 2004, Hasler and Ott 2008).

The other side of the coin is that the development of dive tourism may offer an alternative livelihood to local communities that contributes to coral conservation by discouraging illegal fishing and industrialisation in coastal areas (Cater 2003). Additionally, evidence of the value of reefs as a tourism attraction may increase the environmental awareness of local communities (Dearden et al. 2006, Diedrich 2007). However, tourism managers have limited direct control over the behaviour of operators and tourists and it can be imaged that as long as SCUBA diving or snorkelling is allowed, some damage to coral will occur.

Thus the question is not how to avoid this damage, but how to keep the damage at an acceptable level. In response to the pressure created by marine tourism activities on coral ecosystems a range of management programs and interventions have been developed involving both managers and resource users (D'Angelo and Wiedenmann 2014). These include public education programs on reef conservation (Courtney and White 2000), modifications to local regulations (Wongthong and Harvey 2014), and closures to protect reefs and the ocean floor from the impacts of fishing (Wilkinson and Brodie 2011), among others. Additionally, international agreements have been reached and guidelines issued to regulate the trade in coral reef wildlife (Dee et al. 2014). Strategies for coral reef conservation include command or control methods (e.g. limiting visitor numbers, zoning plans, and environmental education), economic instruments (e.g. eco-labelling, conservation taxes) and ecological tools (e.g. coral restoration, ecological monitoring programs).

However it is generally agreed that management plans should be based on a systematic in-depth understanding of coral based dive tourism from a social-ecological system (SES) perspective and, equally importantly, fully involve local stakeholders (Fabinyi 2008, Zagonari 2008, Wongthong and Harvey 2014).

1.3 Complexity of social-ecological systems

In recent years, as a relatively new concept, SES analysis has received increasing attention as a conceptual framework for the conservation and management of natural resources. This approach emphasizes the integration of knowledge about humans and nature, dimensions that were more often treated as isolated topics until the late 1990s (Berkes and Folke 1998). Various definitions of "social-ecological system" have been proposed by researchers from different disciplines and/or for use under different circumstances. Here I adopt the definition given by Glaser (2012), a social scientist whose work focuses on sustainable livelihoods in coastal and marine areas: "A social-ecological system consists of a bio-geophysical unit and its associated social actors and institutions. Social-ecological systems are complex and adaptive and delimited by spatial or functional boundaries surrounding particular ecosystems and their problem context".

From this perspective, when studying the impact of tourism on coral ecosystems, it is important to consider that dive tourism and the associated coral reefs form a complex social-ecological system with both ecological (nature) and social (human) dimensions. Studies that consider only one or other of these dimensions fail to present a holistic picture and lack the knowledge integration that is essential for sustainable coastal management (Forst 2009, Ferrol-Schulte et al. 2013). It is imperative that scientific research generates knowledge about both social and ecological processes and the relationships that exist among their specific components and variables. Understanding the dynamics of complex SES characterized by human exploitation, such as coral reef systems, also requires investigation of interactions and feedback mechanisms (Van Vliet 2010, Castelletti et al. 2010) among different spatial and temporal scales. These are the keys in order to comprehend the non-linear processes which link the ecosystem to human decision-making. This integrated knowledge provides the foundation for a comprehensive conceptual system, and inputs for the development of collaborative strategies and/or conflict resolution mechanisms. To achieve this objective, multiple methods need to be employed. A growing number of innovative methodologies and concepts for analysing SES have been developed in the last decade, including hotspot mapping (Alessa et al. 2008), mediated modelling (Antunes et al. 2006), social metabolism (Martinez-Alier et al. 2010) and crafted rules (Thiel et al. 2015). Role playing games, in which participants explore the outcomes of collaborative and competitive social interaction, combined with computerized agent-based modelling (ABM), simulating the actions and interactions of individuals or collectives, have been widely and successfully applied as inputs for sustainable resource management, especially in terrestrial environments (Castella et al. 2005, Guyot and Honiden 2006, Ligtenberg et al. 2010). More recently, the SES concept has increasingly been applied in studies of coastal and marine environments, including coral reefs (e.g. Cinner et al. 2012, Kittinger et al. 2012, Freed 2013, López-Angarita et al. 2014).

1.4 Participatory approach

It is generally accepted that the integration of information on social and environmental dimensions of SES requires participation of the resource users. A participatory approach seeks to engage local stakeholders in all stages of the management process from research to project development and implementation. This is especially important when the aim is sustainable management of natural resources, since the livelihoods of the local communities depend on maintaining the health and productivity of the living environment (Glaser et al. 2010). The concept of participation is widely adopted as a guiding principle of management practice in a variety of contexts including e.g. land use planning (Volkery et al. 2008), and public sector decision making (Kim 2007), budgeting (Rose et al. 2010), and evaluation (King 2007). In the academic world, Wadsworth (1998) made suggestions to improve participatory research in late 1990s. She advocated that local knowledge should no longer be treated as supplementary, but should form the basis of planning and decision-making processes. This approach has been widely adopted by researchers, for example, in the fields of health care (Cornwall and Jewkes 1995) as land use (Castella et al. 2005, Fürst et al. 2014), as well as coastal ecology (Allmendinger et al. 2002, Diedrich 2007, Cleland et al. 2010). As a new paradigm for management and research, the participatory principle has in turn stimulated the development of new, innovative or cross-disciplinary approaches (Lynam et al. 2007), such as fuzzy cognitive mapping (van Kouwen et al. 2008), role playing games (Ligtenberg et al. 2010) and agent based modelling (Bousquet et al. 1998, Guyot and Honiden 2006). These provide a range of methodologies for operationalizing the integration of local knowledge and values in decision making (Mendoza and Prabhu 2005).

1.5 Agent-based modelling

Different combinations of local, regional and global stressors and the biogeographic settings of individual reef areas all interact in complex ways that affect both the current condition and future of reefs. To meet the need for the proper management of such complex systems, agent-based modelling (ABM; also called individual based modelling) is recognized as a promising tool. ABM is a flexible approach that can produce relatively realistic simulations of complex situations, as well as providing new opportunities for transdisciplinary knowledge integration and the participation of decision makers (Worrapimphong et al. 2010, Glaser 2012, Rounsevell et al. 2012).

Even though the basic idea of ABM was developed in the 1940s, since it requires computation-intensive procedures, the first models were not published until the 1970s (Schelling 1971, Grimm et al 2005). Early in the 1980s, ABM was used for research on complex dynamics, and specifically as a tool for the representation and simulation of ecological phenomena (Jopp et al. 2011), mainly because it allows a spatial representation of heterogeneous entities with individualistic behaviour in a heterogeneous environment (Breckling 2002, Reuter et al. 2010). An agent-based model can be designed to represent detailed system components and processes on different integration levels to recreate the dynamics of that system as a whole (Breckling et al. 2006, Grimm et al 2005). It requires a ‘micro-to-macro’ way of thinking with dynamics on higher integration levels emerging as self-organized properties (Fig 1.1). By focusing on individual behaviour and interactions among individuals, ABM creates a dynamic system with a variable interaction structure, which develops according to defined rules. Outcomes are generated as processes arising from the self-organized actions of numerous interacting agents (Breckling et al. 2006, Reuter et al 2011) .

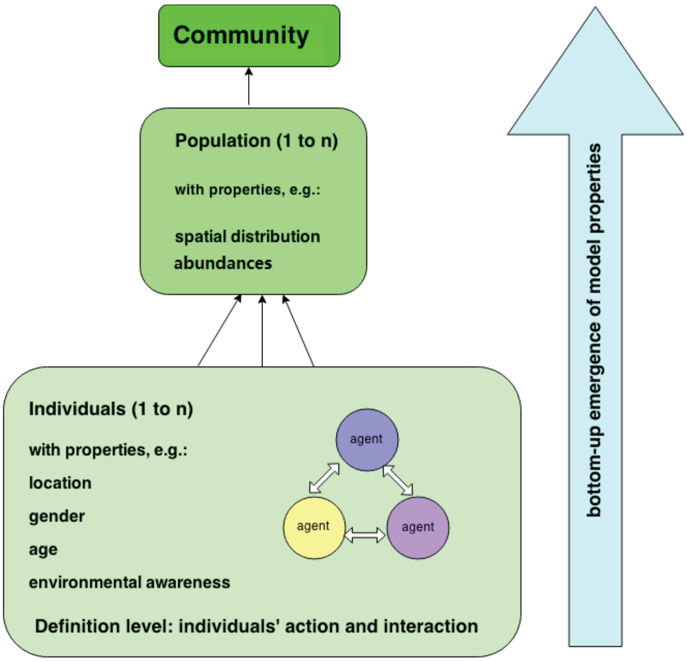

Figure 1.1: An example of an agent-based model from an ecological perspective. In this model, a cycle of the dynamics of higher organizational levels (populations and community) arises as a result of repeated interactions among individuals (agents) with distinct properties. Model dynamics are mostly defined on the individual level, which thus constitutes the definition level of the model (Adapted from Reuter. 2005).

Innovations in computer technology, especially the development of object-oriented programming (OOP) has made ABM programming easier in recent decades. OOP provides a framework for structured programming, based on calculation of and communication between classes or blocks of codes. In OPP, "objects" with particular properties and attributes can be defined with their internal states, characteristics and their relation to other objects, which are self-contained with respect to their data and controls. Use of OOP enables ABM to generate more realistic simulations of biological and/or human relations and interactions in a dynamic environment. Development of an agent-based model is an iterative process, rather than a linear one, involving repeated cycles of knowledge gathering (e.g. literature review, empirical data collection), development of rules for simulation (programming) and application and review of the model (scenario testing, ground truthing) until the model's behaviour and the results are deemed satisfactory by stakeholders. Iterative modelling with stakeholder participation allows different voices (e.g. those of the government and local communities), perspectives and even decision-making processes to be incorporated into the model. Such involvement of resource users is essential for regional coastal management (Glaser et al. 2010, Glaser 2012). Nowadays, ABMs are widely applied by researchers working in different disciplines including biology and ecology (Reuter et al. 2011), economics and social sciences (Defreitas et al. 2013), and management (Jin et al. 2007). In the marine environment, natural scientists have employed ABM to describe and explain the dynamics of non-human life forms (Kubicek et al. 2012, Reuter et al. 2016), while many other studies deploy ABM (or IBM) to investigate human behaviour (McDonald et al. 2008, Worrapimphong et al. 2010). A smaller number of studies apply ABM to develop an in-depth understanding of dynamics between human and natural components in coupled social-ecological systems (Cabral et al. 2010, Gao and Hailu 2013).

1.6 Study area: Koh Tao

Koh Tao (Thai: เกาะเต่า, Thai pronunciation: [kɔ̀ʔ tàw], lit. "Turtle Island", location 10° 5′ 38″ N, 99° 50′ 11″ E) is an island in Thailand and forms part of the Chumphon Archipelago on the western shore of the Gulf of Thailand (Fig. 1.2a). It covers an area of about 21 km². Administratively it forms a district of Surat Thani Province. Picturesque coral reefs, marine life and affordable diving courses and the large number of dive schools make Koh Tao a primary diving destination in Thailand (Flumerfelt 1999) .

Figure 1.2: Map and photos of Koh Tao, Thailand. (a) Koh Tao and (inset) its location in the gulf of Thailand. (b) Beautiful coral reefs are an attraction for dive tourism. (c) Koh Nanyuan is the most popular tourist site on Koh Tao. Pictures were taken by the author.

In the past, Koh Tao was used as a political prison. At the same time, local people settled the island and introduced fishing, coconut palm plantations, rice paddies and orchards. The Koh Tao community comprises a small, but growing resident Thai population. The island has three villages, whose resident population of 1097 people in 2003 had risen to 2106 by 2012 (Wongthong and Harvey 2014). Traditional small-scale and recreational fishing occur widely on Koh Tao, but large-scale industrial fishing boats rarely venture into the no fishing zone of 3 km around the Koh Tao Island (Worachananant et al. 2008).

Thailand's coastal waters, located between 6° and 13°N, provide good conditions for coral reef growth. Surveys carried out in waters surrounding Koh Tao in 2005 found that the average density of juvenile colonies was 6.44/m^2. *Fungia* spp., *Pocillopora damicornis* and *Echinopora lamellosa* were the dominant coral species; other common coral recruits were

Pavona sp., *Porites* spp., *Goniastrea* spp., *Favites* spp., *Leptoria* sp. And *Montipora* spp. (Yeemin et al. 2006). The diverse ecosystem of these coral reefs form over 30 natural dive sites for snorkelling and SCUBA diving activities (Fig.1.2b). In the 1980s, the first tourists came to this island. Since the 1996/97 season, there has been a boom in dive tourism development: the number of dive schools rose from only 6 in 1996 to 20 in 2000 (Korn,2010). Today, 59 dive schools, 132 restaurants, 75 retail stores, 29 wellness centres and 70 other service establishments (tattoo parlours, photo studios, etc.) serve around 400,000 annual visitors the island (TAT, 2014). The island's economy is based largely on diving and reef related tourism, which generate a revenue over 2 billion Baht[1] (47 million Euro). In 2006, 50% of current diving certificates in Thailand were issued in Koh Tao (Larpnurn et al. 2011). The large number of SCUBA divers, who come to the island for dive courses leading to certification, are drawn by the calm sea, tropical climate, and very reasonable prices. Previously, two main events drew other tourists to the island: the Full Moon Party (Fig. 1.3a), which occurred every month, and the Koh Tao Festival that takes place every June (Fig. 1.3b). Full-moon parties were banned following the murder of two tourists on the island in 2014, but visitors to Koh Tao are still able to get a boat across to the world-famous Full Moon Party on the neighbouring island of Koh Pha-Ngan. The low season for tourism is the monsoon season between November and January, which forces closure of dive sites on the east side of the island and discourages general tourism (Fig. 1.3c).

Figure 1. 3: Activities and natural disaster on Koh Tao. (a) The Full Moon Party on Koh Tao, discontinued in 2014. (b) Film show at the "The Experience Festival" on Koh Tao. (c) Strong storms may affect Koh Tao in the monsoon season between November and January. Pictures were taken by C. Scott.

As in many other developing regions throughout the world, tourism in Koh Tao is oriented primarily towards economic development without full consideration of the longer term consequences of the development and consideration of sustainable management (Churugsa et al. 2007). Socio-culturally, the large numbers of migrants, a progressively higher cost of living and the introduction of drugs and night life activities can be listed as detrimental factors (Churugsa et al. 2007, Wongthong and Harvey 2014). Ecologically, since tourism development on this small island started, a notable degradation of coral communities has been observed by local ecologists (Yeemin et al. 2001) and government agencies (DMCR 2010a). The health of coral around Koh Tao was rated very good or good (using live coral and dead coral coverage ratio as indicator) by DMCR from 1987 till 1997, but fair or bad since then. Results of a more detailed survey carried out in 2006 using the photo line-intercept transect (PLIT) method indicated that benthic cover of coral reefs around the island consisted of 20.42%

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[1] 1 Euro ≈ 40 Baht, in 2011.

live coral, 16.35% dead coral and 23.52% rubble (DMCR 2010a). The declining heath of Koh Tao's coral reefs has been confirmed by both Reef Check (an international non-governmental organization dedicated to the conservation of reef ecosystems) and the Koh Tao local Environmental Monitoring Program (EMP) during author's participative observation and communication, which continuously records the coral health status at multiple dive sites around island using linear transects technique (Fig. 1.4d). In general, reefs in shallow zones are more degraded, and an increased abundance of macro-algae has been recorded in certain areas. Partial mortality of massive corals, i.e. coral heads (affecting e.g. *Favia* spp., *Favites* spp. and *Porites lutea*) is clearly evident in shallow zones of certain study sites, such as Sai Ree Beach and Chaloak Bankao Bay (Yeemin et al. 2001, Hein 2012).

A decline in coral health can be caused by both natural and human factors. The severe coral bleaching events in 1998, 2002 and 2010 resulted in high mortality rates for several coral species, especially *Acropora* spp. Periodic typhoons have caused patchy coral damage at individual reef sites (Tun et al. 2008, Hoeksema and Matthews 2011). A variety of anthropogenic drivers—such as land development, wastewater discharges, increased sediment in the water, trampling by divers, and anchoring—have resulted in more widespread degradation of coral communities (Franke 2009, Hein 2012). Most indigenous and long-term residents of Koh Tao are aware of these problems and understand the need to take measures to preserve the island's natural environment (Scott 2012). The NGO *Save Koh Tao*, which represents local business owners, dive instructors, lawyers, school teachers, fishermen and other representatives of Koh Tao's indigenous community, has mobilized local people to take action to conserve the terrestrial and marine environment. Initiatives such as regular beach and underwater clean-ups (Fig. 1.4a), coral health monitoring and restoration programs (Fig. 1.4c & d), and eco-labelling awards for pro-environmental dive schools (Fig. 1.4b) raise environmental awareness and provide opportunities for local business operators, government officials and visitors to get involved in conservation. However, passion and local actions such as these will not necessarily lead to efficient environmental protection. For local residents, NGOs and researchers, the principal challenge remains the long-term sustainable management of the island and its resources; this will only be possible based on a deep scientific and holistic understanding of the social-ecologic system on Koh Tao (Yeemin et al. 2006, Churugsa et al. 2007, Wongthong and Harvey 2014).

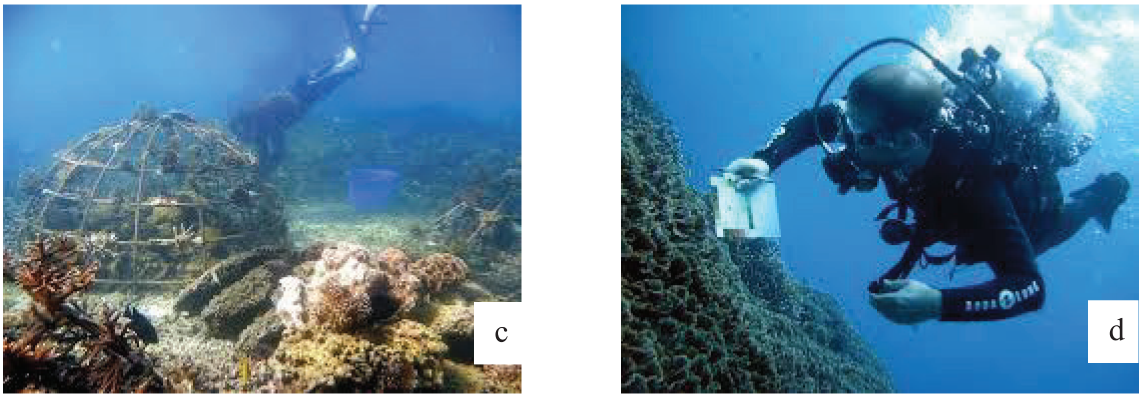


Figure 1.4: Activities organized by the NGO *Save Koh Tao*: (a) beach cleaning event group picture; (b) dive school advertising with eco-labelling; (c) underwater coral restoration activities; (d) environmental monitoring activities. Pictures (a, c & d) were taken by C. Scott. and picture (b) by author.

1.7 Research objectives

In addition to the impacts of global environment change, coral reefs face many threats from different types of usage on the local scale. Tourism can impact reefs either directly (e.g. when divers break corals) or indirectly (e.g. through discharge of untreated waste water, and increased demand for reef fish). While the effects of global and local-scale disturbances on coral reefs have been the focus of several reviews (e.g. Hughes et al. 2003, Hoegh-Guldberg et al. 2007), few studies have attempted to formally analyse how global stressors such as climate change, interact with local ones (Jackson et al. 2001, Halpern et al. 2008). As a result, very little is known about relative roles of global stressors and disturbances caused by local tourism development, or their interaction as drivers of change in coral reef systems.

This is a key issue in Thailand, since intensive marketing and promotion have made the country one of the world's most successful, fastest-growing tourism destinations in terms of visitor numbers. However, lack of proper planning, failure to implement regulations, a long tradition of 'top-down' management, and a general lack of concern about the possible negative impacts of tourism have all contributed to a measurable degradation of socio-cultural and environmental resources, including coral reefs, at tourist destinations throughout the country (Ruangsawang and Yeemin 2003, Wongthong and Harvey 2014).

As mentioned above, Koh Tao is one example of the rapid growth in tourism in Thailand: Over a few decades, this once sparsely populated island has developed into a major tourism destination, with more than 50 dive schools currently operating there. It has to be assumed that tourism has important direct and indirect impacts on local coral reefs. Regulations as well as other management measures are urgently required in order to avoid severe environmental damage in the near future.

Gao and Hailu (2012) note that management measures undertaken to address pressure from human activities on natural resources are most often developed on an ad-hoc basis; they are rarely supported by the systematic assessment of alternatives and even less so by dedicated modelling, despite the evident need for such approaches.

Thus, the objectives and key research questions of this project are:

1. To develop an agent-based model (called ‘KohTaoSim’) of a dive tourism-related SES (hereafter “dive tourism SES”), using Koh Tao, Thailand as a case study.

   Research questions:

   - What are the key components/linkages and influential variables/processes in such an SES?
   - How can qualitative and quantifiable knowledge derived from empirical study be transformed into an ABM?
   - Can stakeholders’ opinions in this SES guide the model development process? Through what mechanism?

2. To analyse the implications of dive tourism for coral reefs, in conjunction with other local and global threats.

   Research questions:

   - What main feedback loops affect the relationship between coral reef health status and tourism?
   - What are the effects of global and local stressors on the dive tourism SES? How do these stressors interact with each other?

3. To evaluate the implications of different management schemes on sustainable use.

   Research questions:

   - Will reducing coastal pollution from tourism on coral ecosystems (e.g. through reforestation, implementation of waste water plants) improve coral health and generate economic benefits?
   - Does the construction of artificial reefs have the potential to improve coral health and generate economic benefits? Where artificial reefs should be located in order to maximize ecological and economic benefits?
   - To what extent does the eco-labelling scheme contribute to more sustainable patterns of coral reef use, improve the experience of visitors and generate economic benefits for the tourism sector?
   - What are the likely ecological and economic outcomes of improved environmental awareness among tourists who visit Koh Tao?
   - Is there a need to control visitor numbers on the island? If so, how should this be done and at what level should limits to visitor numbers be set?

4. To offer key features of a sustainable tourism management plan for Koh Tao based on SES analysis using KohTaoSim.
5. To summarise the advantages and drawbacks of this participatory agent-based modelling approach for dive tourism management, based on the experience of this study.

Chapter II: METHODS

2.1 Overview

ABMs have a unique potential to unravel hidden feedback mechanisms in coupled SES. However, in order to be able to understand and evaluation model outcomes, it is important to explicitly address the assumptions behind the methods and processes employed and the derivation of the variables incorporated in the model (Schlüter et al. 2012). Although in principle an ABM could be constructed based on theories or empirical observations, reviews of ABMs suggest that they are generally based on conceptual principles rather than on parameters/algorithms derived from empirical data. In other cases, the models are not sufficiently developed and/or documented to show how the data they are based on has been derived, especially with respect to the degree of stakeholder participation in model development (Smajgl et al. 2011).

In this section, I provide an overview of the participatory process leading to the development of an ABM, which I call KohTaoSim, which uses field data from the Thai island Koh Tao to simulate the effects of dive tourism (i.e. snorkelling and SCUBA diving) on a coral-reef ecosystem. My model draws on a generic suite of information about the island while incorporating relevant information from resource users' experiences and viewpoints in order to provide inputs for better management of coral reefs. I synthesized available societal and social science knowledge into KohTaoSim following an iterative modelling method, commonly called 'companion modelling' (Gurung et al. 2006) in social science research. Fig. 2.1 is a schematic representation of the steps in the iterative modelling process; in reality the iterative loops cycled in a non-linear manner between the steps of the process until stakeholders were satisfied by the model behaviour and its outcomes.

In what follows, I first present the results of my empirical investigation focused on the research question concerned with the key components/linkages and influential variables/processes in Koh Tao dive tourism SES. This empirical social research was conducted through semi-structured interviews with key informants (n = 20), surveys of selected tourists (n = 246), focus group discussions (n = 4), and observations made in various areas of Koh Tao. A novel aspect during this stage of the process was the incorporation of a role playing game, conducted in 2 rounds of sessions with the participation of representatives of local SCUBA dive schools, dive tourism companies and local NGOs. Participation in the game enabled local stakeholders to gain a holistic perspective on the social and environmental consequences of individual actions related to coral reefs and their resources (Glaser 2012). Then I discuss in more detail how data derived from qualitative and quantitative social field research informed the development of a model, used in combination with secondary ecological and social data. This is followed by an explanation of technical, computational and simulational details of the ABM, including how systematic sensitivity analysis was used to refine and specify the parameter values. Finally, the chapter ends with description of model validation procedures and scenario settings.

2.2 Participatory approach and iterative processes

> *"The key element of participatory research lies not in methods but in the attitudes of researchers."*
>
> *------- Olivier Barreteau 2013*

The development of KohTaoSim, as a model of a coral reef based dive tourism SES was undertaken in an iterative process comprising two sequential phases of empirical social research on Koh Tao, between which the major part of the computational development of the model took place (Fig. 2.1). This iterative modelling method of KohTaoSim provided the opportunity for involvement of resource users and stakeholders at all stages of the research.

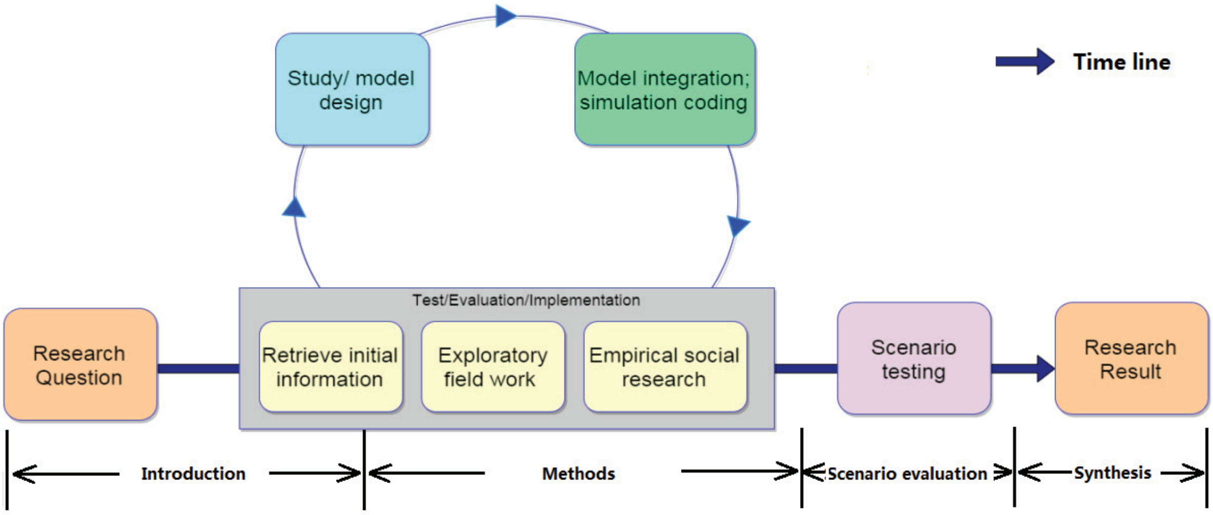
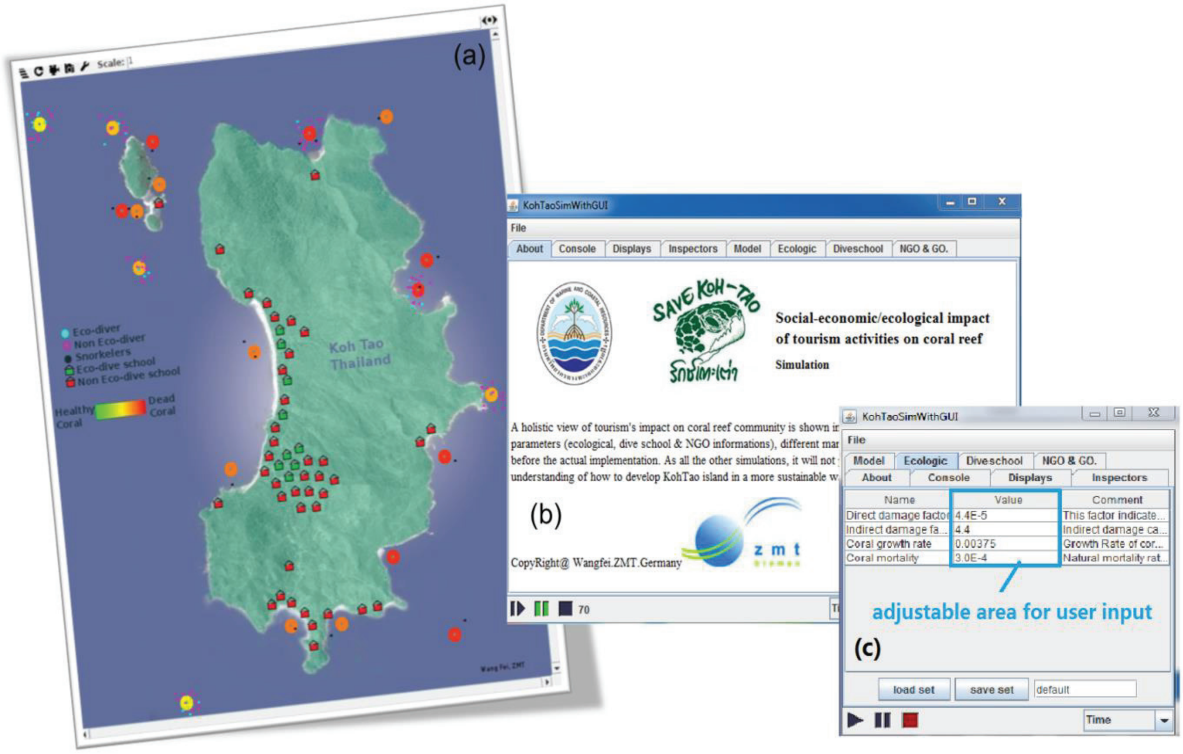


Figure 2.1: Iterative modelling process for the development of KohTaoSim.

Principal features of the participatory model development, described in detail in the remainder of this chapter, were as follows:

- At the beginning of the research, in-depth interviews were conducted with the local coral reef ecologist and coordinators of the local NGO *Save Koh Tao*. Their opinions, for example on the need for scientific research to inform improved management of dive tourism on Koh Tao, and on key current issues and challenges, provided important inputs for the formulation of the research questions.
- The initial design of KohTaoSim, based mainly on a review of relevant literature, was discussed with 4 regional experts. KohTaoSim presents a simplified view of a coral-based dive tourism SES and, inevitably, a lot of assumptions had to be made to enable this simplification. The experts reviewed these underlying assumptions and made suggestions to improve the model.

- Discussion between the researcher and participants during empirical field work enabled unreasonable and unrealistic behaviour of the model to be identified and for appropriate changes to be made to the model algorithm and parameters.
- Key informants and stakeholders involved in this study had the opportunity manipulate KohTaoSim and observe its behaviour via a user interface (Fig. 2.2) during role playing games. Information (model configuration files and personal opinions) obtained during the role playing games informed on the specification of model parameter values for both ecological and social dimensions.
- To reach a consensus among all participants that KohTaoSim was "ready", the revision processes described above went through several iterations. The explicitly participatory procedure for validating, i.e. ground truthing draft versions of the model enabled the concerns of those who directly depend on and use the coral reefs to be incorporated.
- Scenarios for testing the model were selected based on the management ideas put forward by local NGOs and local government agencies.
- As an integral part of the participatory process, the results of the research will be made available to local stakeholders as a frame of reference for their management decisions aimed at the sustainable development of reef tourism on the island.



Social-economic/ecological impact of tourism activities on coral reef

Simulation

A holistic view of tourism's impact on coral reef community is shown ir
parameters (ecological, dive school & NGO informations), different mar
before the actual implementation. As all the other simulations, it will not
understanding of how to develop KohTao island in a more sustainable w

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Name	Value	Comment
Direct damage factor	4.4E-5	This factor indicate...
Indirect damage fa...	4.4	Indirect damage ca...
Coral growth rate	0.00375	Growth Rate of cor...
Coral mortality	3.0E-4	Natural mortality rat...

Figure 2.2: A screenshot of KohTaoSim's user interface: (a) One of the simulation display windows, which provides a dynamic representation of coral status and diving activities on the island. The map shows selected dive schools and dive site locations based on data from 2012. (b&c) Control panel for general adjustments and specific parameter changes. This is the platform for local stakeholder involvement in setting model parameters.

2.3 Social study: data collection methods

I collected data during two periods of field research, in 2012 and 2013, using the following methodology: (1) semi-structured interviews with key informants, (2) a structured questionnaire administered to tourists, (3) focus group discussions, (4) role playing games, and (5) observations made in various areas of Koh Tao.

2.3.1 Semi-structured interviews

The semi-structured interviews covered issues related to the general social-economic characteristics of communities, status of coral reefs, environmental awareness, knowledge of activities of NGOs, and tourist preferences such as type of accommodation, the presence of environmentally friendly dive schools, and the availability of different kinds of dive facilities on Koh Tao. Appendix 1 provides the list of the questions used; an informal semi-structured approach was adopted that allowed interviewees to diverge from the topic to provide other relevant information. In total, 20 key informants were interviewed. These included coral-ecologists (3), dive school and snorkelling tour company owners and managers (4), NGO leaders and coordinators (3), and tourists (10). They were selected to give a perspective on local communities in the area, on issues related to coral reefs and marine environment, and on current diving activities on the island and related supporting services.

2.3.2 Structured questionnaires

To procure quantitative data for the ABM, 246 tourists were interviewed. Respondents were selected randomly while they were waiting for a ferry to leave Koh Tao. Interviews using a survey questionnaire (Fig. 2.3, Appendix 2) were carried out during the day and in the evening. During daytime, when there were usually two benches in the waiting area at the ferry pier, every third tourist starting from the end of the pier side of the benches was approached and interviewed. During evening time—when no waiting bench was available and passengers could directly board the ferry—every fifth tourist on each row of benches on the ferry was asked for an interview. Data were collected on social-economic characteristics of tourists including gender, age and nationality, travel information and general satisfaction with tourism services offered on the island. Divers were asked for their opinions on the dive schools, services offered and the diving experience, as well as questions intended to assess their environmental awareness, satisfaction with the health of coral reefs and willingness to pay for marine conservation. There was great cooperation and no one refused to respond.

Figure 2.3: Tourist filling out the questionnaire in the ferry waiting area before departure from Koh Tao.

2.3.3 Focus group discussions

Two separate rounds of focus group discussions, each with four participants, were conducted to provide information complementary to and comparable with the empirical data from interviews. Each round consisted of two focus group meetings: one with instructors, dive masters, owners and managers from eco-labelled dive schools and the other one with similar participants from non-eco-labelled dive schools (Fig. 2.4). For the first round, the aim was to focus on important differences between eco- and non-eco-labelled schools regarding the definition, scope and appropriateness of dive operations and education of divers and tourists. Discussions addressed the eco-labelling process, and factors influencing the choice of preferred dive sites for different activities. The second round of focus group meetings took place a year later after the basic simulation of Koh Tao dive tourism had been developed. These discussion groups where used for validation of the model in a way that is functionally equivalent to ground truthing. This constitutes one of several methods to ensure correctness of a model and its functionality (Kubicek et al. 2015). The discussions in the focus group were noted down (in English language) by the researcher for further analysis.

Figure 2.4: Focus group discussions with dive school owners and staff.

2.3.4 Role playing game

The purpose of role playing games in the research was to confirm the reliability of model behaviour and to parameterize factors relating to the dive schools (e.g. cost and profit per SCUBA dive) and the GO/NGO (e.g. the minimum donation required from a dive school to the NGO in return for eco-labelling). The first role playing game was conducted individually with three key informants from the GO/NGO (Fig. 2.5); the second game was played with instructors, dive masters, managers and owners from dive schools during the second round of focus group meetings. At the beginning of each role playing session, participants were informed about the principal features of the KohTao simulation model. Participants discussed the model with the researcher and agreed on the parameters relevant to the group they belonged to (e.g. dive school or GO/NGO). Participants were asked to estimate values for these parameters (e.g. the parameters for the dive school group included profit per dive, cost of a dive certification course, and number of divers per group). These were saved into a configuration file for later analysis, as well as to provide inputs for running the model. Participants observed the simulation through the user interface of the model, and were asked to comment on the extent to which the model satisfied their expectations. All participants in these role playing games were willing to share their knowledge and freely offered their opinions on initial values in the model.

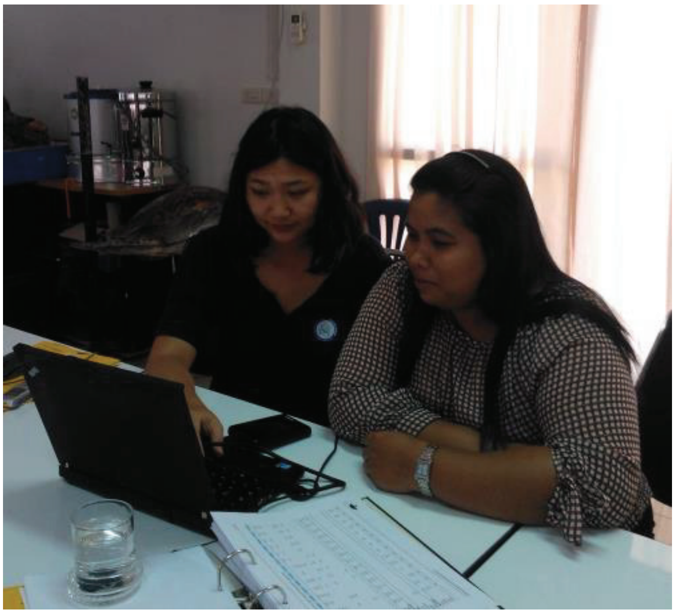


Figure 2.5: Role play with KohTaoSim during the key Informant interview with the local coral ecologist (right).

2.3.5 Participant observation

Participant observation was undertaken during numerous exploratory walks on Koh Tao and sessions in both eco- and non-eco dive schools and as a participant in SCUBA diving courses. During the walks, price lists for services offered by both eco- and non-eco-labelled schools were collected and differences between eco- and non-eco schools highlighted during focus group discussions (e.g. group size, price, the extent to which schools offered marine conservation education) were further explored. Additional information for this study was collected in telephone interviews with all 55 dive schools on Koh Tao to collect information about prices and usage of dive site locations.

2.4 Incorporation of social science knowledge into the model

The qualitative information from semi-structured interviews, focus group discussions, role-playing games and observations was used together with the quantitative data from the tourist survey to develop parameters, algorithms and rules for the ABM of coral reef based dive tourism on Koh Tao.

Interviews revealed a complex web of interactions between social actors in reef tourism (dive schools, tourists, the NGO and the government) and between social actors and ecological components (coral reefs) on Koh Tao. The roles of social actors on ecological conditions differed markedly. It is essential to take account of this kind of complexity when modelling behavioural choices (Gilbert and Terna 2000). In the following section, I explain how the social science data was integrated into the ABM during the development of KohTaoSim.

2.4.1 General description of the model

The complexity of stakeholder interactions made it clear that it was essential to move beyond simply considering the effects of interventions by stakeholders in isolation (for example, attributing coral damage to diving activities) in order to adequately represent the multi-dimensional dynamics of the local context. The model represents the interactions of the different actors (individuals and groups) at a high temporal resolution of half a day and incorporates their context dependent decisions. The dynamics of the marine (coral reefs) and social environment (divers and dive schools) are simulated spatially, with changes occurring at specific locations (dive sites and dive schools) in response to different forms of use.

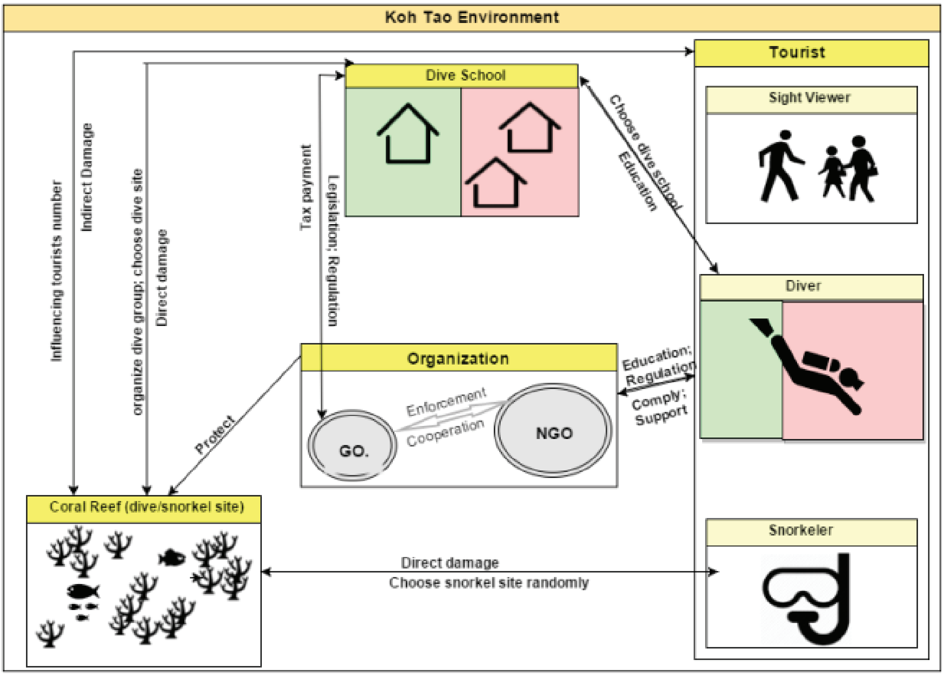


Figure 2.6: Conceptual model structure for KohTaoSim representing agents and their interlinkages. The model incorporates the different roles of key stakeholders in marine based tourism.

Since Koh Tao is a coral based dive tourism destination, the status of coral is undoubtedly influential on tourist numbers. On the other hand, diving activities will also cause the direct or indirect damage to coral. Snorkelers may randomly choose a snorkelling site near the coast. However, divers will need to choose a dive school and then accept the dive school's choice of dive location. The interaction between NGO, dive school and tourists is represented as contributing to the conservation of ecosystem, for example by developing ecotourism, and as essential to set in motion a series of actions to inform and educate visitors and residents and to promote proper management and use of coral reefs. For example, pro-environmental divers are more likely to choose pro-environmental dive schools; Dive schools make a decision whether to get an eco-label from the NGO once a year, taking account of the perceived costs and benefits involved. The dive site selection criteria and priorities are different in non-pro-environmental to pro-environmental dive schools. Government actors can support the NGO by funding its conservation projects. However, government capacity is rather low (Worachananant et al. 2008). Fig. 2.6 illustrates an overall structure of KohTaoSim, which was developed in JAVA using the Mason library (version 16).

2.4.2 Agents and entities

Information from the survey, the literature review, and the discussions with key informants indicated that the tourist industry in the study area involves a complex web of social-ecological interactions driven by social actors (dive schools, tourists, the NGO and the government) and also by coral reef dynamics. These social actors and environmental elements are denoted as agents in the model, each with different properties, a range of actions that are taken in different circumstances, and interactions with other agents. In the case of human agents, these properties and actions are influenced, crucially, by perceptions and values. For example, key informants explained that whether or not stakeholders were pro-environmental, and considered themselves to be so, was the key factor influencing their behaviour. Understanding how characteristics of agents influence their behaviour is crucial to inform decisions on the selection of agent types and associated variables, in order to improve process representation in the model. The following sections describe the agents in KohTaoSim and explain the selection of variables for inclusion in the model.

Social agents

Tourists

The basic function of tourists, as essential actors in this complex system, is to come to Koh Tao and leave at end of their stay. The development of the agent rules for our model is based on the social-demographic characteristics of the study respondents. Interestingly, 70% of the people interviewed were from European countries. This may be attributed to the fact that during the time period of this research, Europeans with their preference for tropical regions during winter in their home countries were in Thailand for their end-of-year holidays (Table 2.1). We did not discover any statistical dependence of marine-based tourism activities on age, gender, origin or frequency of visiting within the sample. Consequently, these were not selected as variables for definition of this group of agents (i.e. tourists).

Table 2.1: Social and demographic characteristics of the survey respondents (n = 246)

Variables	Percentage (%)
Sex	
Male	52
Female	48
Age range in years	
<20	4
20-30	57
30-40	23
>40	16
Origin of visitor (continent)	
Europe	70
North America	9
Asia	8
Australia	6
Others	7
Times of visit	
First time visitors	81
Repeat visitors	19

Eco- or non-eco tourist

About half the respondents to the tourist survey, i.e. 49%, indicated that they had heard about environmental conservation in general. They stated they had been aware of international/local conservation organisations such as WWF, UNEP, etc. before their arrival in the study area. Just over a quarter, i.e. 26%, reported that they had supported general environmental conservation in various ways, such as through charity contributions and membership subscriptions to clubs and organizations dealing with environmental protection. When asked whether they knew of conservation activities on Koh Tao, only 24% of all respondents stated that they had heard of eco-dive schools and the conservation NGO during their time on Koh Tao; while 7% reported that they had taken part in environmental activities during their visit. As found in other studies in Belize (Diedrich 2007) and Thailand (Dearden et al. 2006, 2007), providing environmental education to visitors can stimulate them to act in a more environmentally friendly manner and thus to contribute to sustainable tourism development.

Moreover, awareness of environmental conservation activities is positively associated with willingness to pay for marine conservation among tourists. This factor was identified as a significant variable for this type of agent in our model and led to the differentiation between eco-tourists and non-eco tourists.

Sightseer, snorkeler or SCUBA diver

Based on information from the survey, tourists were divided into three categories, as (1) sightseers, (2) snorkelers and (3) SCUBA divers. This enabled a more precise description of relevant patterns of behaviour by tourists.

Even though Koh Tao is world famous as a SCUBA diving destination, responses to the questionnaire indicated that only 37% of tourists were SCUBA divers. The largest group of participants (46%) limited marine-based activities to snorkelling, partially due to weather constraints, while the remainder (17%) were not involved in any marine-based activities but rather took part in night-life activities, mountain biking or simply passed their time relaxing in hotels.

Statistical analysis revealed that mean length of stay varied depending on the type of marine activities (1-way ANOVA, $F = 7.50$, df = 2, p = 0.007). For example, SCUBA divers stayed relatively longer than snorkelers and sightseers. The length of stay for sightseers was the shortest in the study site, mainly ranging from only 1 to 4 days. Over three-quarters of those surveyed indicated that their visit to Koh Tao lasted between 2 and 7 days (Fig. 2.7). Further statistical analysis showed that there was no correlation between length of stay and several other variables including tourist income, gender, nationality, education and other social and demographic factors.

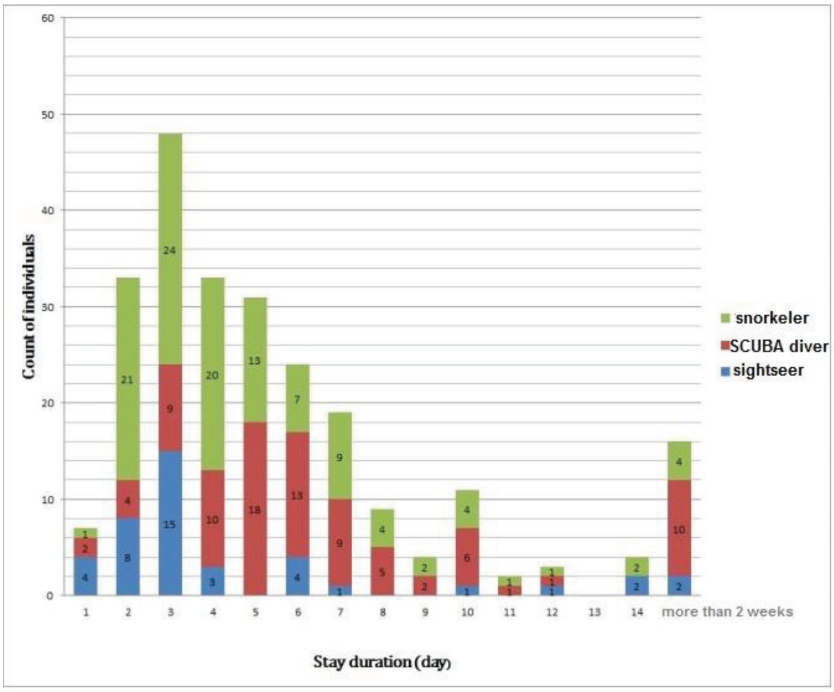


Figure 2.7: Duration of stay on Koh Tao of sightseers, snorkelers and SCUBA divers.

Interestingly, survey results showed that 12.7% of respondents indicated that the large number of visitors on the island (i.e. crowds) was a reason for dissatisfaction after visiting Koh Tao. A larger number of respondents, i.e. 42%, said that they were generally unhappy with cleanliness and suggested respective improvements. Nearly 20% of respondents indicated a low level of satisfaction with infrastructure on Koh Tao, and suggested that improvements in roads, electrical power supply, and sewage were needed. More importantly for this research, 29% of respondents were critical of the overall status of natural resources and proposed management actions to restore and improve the ecosystem status (Table 2.2). While the overall satisfaction of sightseers' was very significantly related to concerns about visitor numbers (Fisher's test, $p = 0.004$), unsurprising SCUBA divers' and snorkelers' overall satisfaction levels were not strongly linked to visitor numbers (Fisher's test, $p = 0.352$), but rather were strongly associated to their perceptions of the status of coral health. This is, in turn, was strongly related to their decision on whether or not to recommend Koh Tao to others (Fisher's test, $p < 0.001$).

Table 2.2: Reasons for tourist dissatisfaction on Koh Tao. This was asked as an open-ended question with the option of giving multiple responses, or none (n = 246)

Reasons	Percentage (%)
Low level of cleanliness	42
Status of natural resources	29
Under developed infrastructure	20
Over crowded	12.7

Sightseers

In general, sightseers took no part in diving activities, but spent their time relaxing in hotels or participating in other activities (mountain biking, night life etc.). In the simulation, they contribute to the total tourist number and cause indirect damage to dive sites (e.g. through increasing marine pollution).

Snorkelers

The behaviour of snorkelers, with regard to their choice of sites is shown in a simplified manner in the model: Snorkelers choose randomly from among snorkelling sites near the coast.

SCUBA divers

Among the interviewed SCUBA divers, 50% were beginners while 50% had limited experience, at most as holders of SCUBA open water certificates. Among the respondents who stated that they were on Koh Tao for SCUBA diving activities, 43% were there for the first level of qualification, i.e. for open-water certification, 14% for advanced open-water certification and 39% were not looking for any new certification. Furthermore, only 4% of SCUBA divers said that they were there for the higher levels of dive qualification (rescue, dive master or dive instructor). Therefore, to simplify the variables in the model, only two level of diving experience are distinguished: open-water and advanced. After divers obtain open-water certification, their level is upgraded to advanced SCUBA diver. An overwhelming majority of dive instructors/masters stated that fun dive groups were operated with less underwater supervision and in larger group sizes than certification groups. Also, more than one-third (36%) of interviewed SCUBA divers used underwater cameras. All three factors may lead to more coral damage during SCUBA dives. Thus, fun vs. qualification dives and underwater camera usage are included into the model as attributes of SCUBA divers.

In contrast to snorkelers, SCUBA divers chose a dive school first and then their choice of location is determined by the preferences of the dive school (for details, see the sections below ‘Dive school assigns dive site’ and ‘SCUBA divers assign dive school’).

Organizations (government and NGO)

NGO

In constructing the model, another important decision concerned the selection of variables to represent the behaviour and influence of the NGO *Save Koh Tao.* The NGO has a direct involvement on environmental conservation on Koh Tao, through activities such as public education programs, eco-labeling, coral health monitoring and restoration. These all require funding. As our interview information suggested, however, money is a big limitation for conservation on Koh Tao. So it seemed reasonable to use the NGO finances as a proxy variable for the impact of the NGO *Save Koh Tao* on the state of the Koh Tao reefs. This numerical information is converted into model rules to specify how much influence the NGO has on dive school and tourist behaviour. A limitation of this approach is that it ignores factors such as the NGO’s efficiency and effectiveness in spending money, nor does it deal with issues related to corruption. Information in the financial log book offered by a key informant revealed that the annual budget for the NGO *Save Koh Tao* was approximately 20,000,000 Baht per year over recent years. This consisted of contributions from the Koh Tao festival (approximately 50%), donations from dive schools (approximately 30%), and other sources. The government contributed only a small portion of the NGO finances, approximately 1,000,000 Baht per year. In discussions and joint calculations with 3 key NGO informants during interviews and role playing games, it was learned that for a dive school to get the eco-label, they would either need to join conservation activities or donate money to cover the labour time and equipment costs involved in verification, which were estimated at about 1,600,000 Baht per year per dive school (SD = 29,439; n = 3). During the Koh Tao festival, all food and drink is prepared by local business owners, but all the revenues from sales of food and drink go to the NGO *Save Koh Tao*, amounting to an average of 1000 Baht per tourist during the festival (SD = 374; n = 3). The NGO uses most of its finances for protection and restoration of corals, education and environmental awareness related activities, and for waste management. When NGO informants were asked about the budget ideally required in order for the NGO to fully implement all its proposed conservation projects, the estimated cost was 75,000,000 Baht per year, representing the sum of all labour, materials and running costs (SD = 20,412,415; n = 3).

In KohTaoSim, the assumption is thus made that the social-ecological dynamics on Koh Tao reef tourism are influenced by the financial situation of the most active promoter of a marine conservation agenda on the island, the NGO *Save Koh Tao*. In the model, NGO funding is positive correlated with environmental awareness among tourism institutions and tourist. It is assumed that if more tourists and businesses are willing to pay the NGO contributions, this will have a positive impact on environmental conservation outcomes through the increase of public environmental awareness on Koh Tao. In more detail, the NGO gets funding from the government, dive schools, tourists (i.e. conservation tax), and the Koh Tao Festival. Technically, the NGO's finance book (a hashtable in JAVA) documents its detailed funding receipts. For example, when a dive school decides to donate to NGO for eco-labelling, this is noted as an income 'from dive school'. The same principle applies to Koh Tao Festival and governmental funding. Thus at the end of the year, the total funding amount from the year can be added up and used to calculate the NGO influence (NGO influence index) for the next year (Eq. 1). The influence index indicates how much influence the NGO has on conservation on Koh Tao. Based on discussions and calculations with key informants on Koh Tao, a 'maximum effectiveness' level of funding is introduced in this function, i.e. an amount sufficient to finance a public education program that reaches all tourists arriving on the island, implement all proposed conservation projects, and pay the staff required to implement these activities. Dividing the previous year's total income by the maximum effectiveness funding yields a rough estimate of the 'influence power' of the NGO. In other words, this algorithm simulates how many conservation projects can be carried out, and the percentage of tourists and business that can be educated, based on the amount of funding received. This value is updated once per year at the end of the year calculated as following, where the maximum value of E_t is 1:

$$(1) \qquad E_t = F_{t-365}/F_{max}$$

$$if\ E_t > 1.0 \quad then\ \ E_t = 1.0$$

E_t : NGO influence index at time t

F_{t-365} : total funding received by the NGO in the previous year (i.e. during the year ending at time t minus 365 days)

$F_{\max}$: 'maximum effectiveness' level of NGO funding (i.e. an amount sufficient to finance a public education program that reaches all tourists arriving on the island, implement all proposed conservation projects, and pay the staff required to implement these activities).

Government

In this simulation, government is a supporting agent without any individual function or attributes. It can increase NGO capacity (i.e. influence in the model) by offering more funding or implement certain management measures, such as imposing controls on visitor numbers (for details see Section 2.7 'Scenarios'). The amount of funding can be adjusted in the control panel in KohTaoSim at the beginning of simulation (Fig. 2.2 c).

SCUBA dive schools

Based on discussions in focus group meetings with instructors, dive masters, owners and managers from dive schools, the functions of dive schools in the model are to attract SCUBA divers, organize dive tours and select dive sites (Fig. 2.8).

Informants had different views on whether differences existed between the two types of dive schools (i.e. eco and non-eco). Several informants considered that the way that dive schools were run was more dependent on the understanding and knowledge of the individuals (i.e. dive school owner or operator) involved. More than half of the key informants felt that conservation awareness on Koh Tao is high because of the large number of conservation activities led by the NGO *Save Koh Tao* and because of the presence of many visitors with a considerable level of marine conservation awareness. More specifically, such positive views of conservation awareness were also linked to the existence and transparent implementation of an eco-label system for dive operators by *Save Koh Tao*. This was seen not only as an indicator of the overall environmental awareness, but also as an essential component of a desired shift towards ecological sustainability. Thus, in KohTaoSim a basic distinction is made between different types of dive school (eco- or non-eco). During the discussions in focus group meetings regarding the motivation for adoption of eco-friendly measures by dive schools, almost all participants agreed that eco and non-eco dive schools do not differ much in ecological commitment *per se*; rather a dive school’s decision to apply for eco-labelling is motivated by profit expectations. Further discussions within the focus groups revealed that economic factors were important in deciding for (or against) being labelled an eco-dive school. Dive school owners asked themselves whether the economic benefits of eco-labelling would outweigh the cost of the donation they were required to make to the NGO *Save Koh Tao* in order to obtain it. However, some key informants, especially dive instructors and dive school managers and owners from non-eco dive schools, complained that the requirements for eco-labelling were too complicated to implement. The detailed decision-making processes involved in getting eco-labelling or not are explained in the section ‘Dive school’s eco-status’.

Forty-nine dive schools are simulated in this model. For simplicity the model does not differentiate dive schools according to their size, services offered, facilities or any other factor. Although informants from the dive schools and tourist questionnaires stated that accommodation facilities can be very important for the attractiveness of a dive school, this attribute is not considered in KohTaoSim. In general, the accommodation provided by dive schools is very basic in comparison with what is offered by hotels and resorts (Wongthong and Harvey 2014).

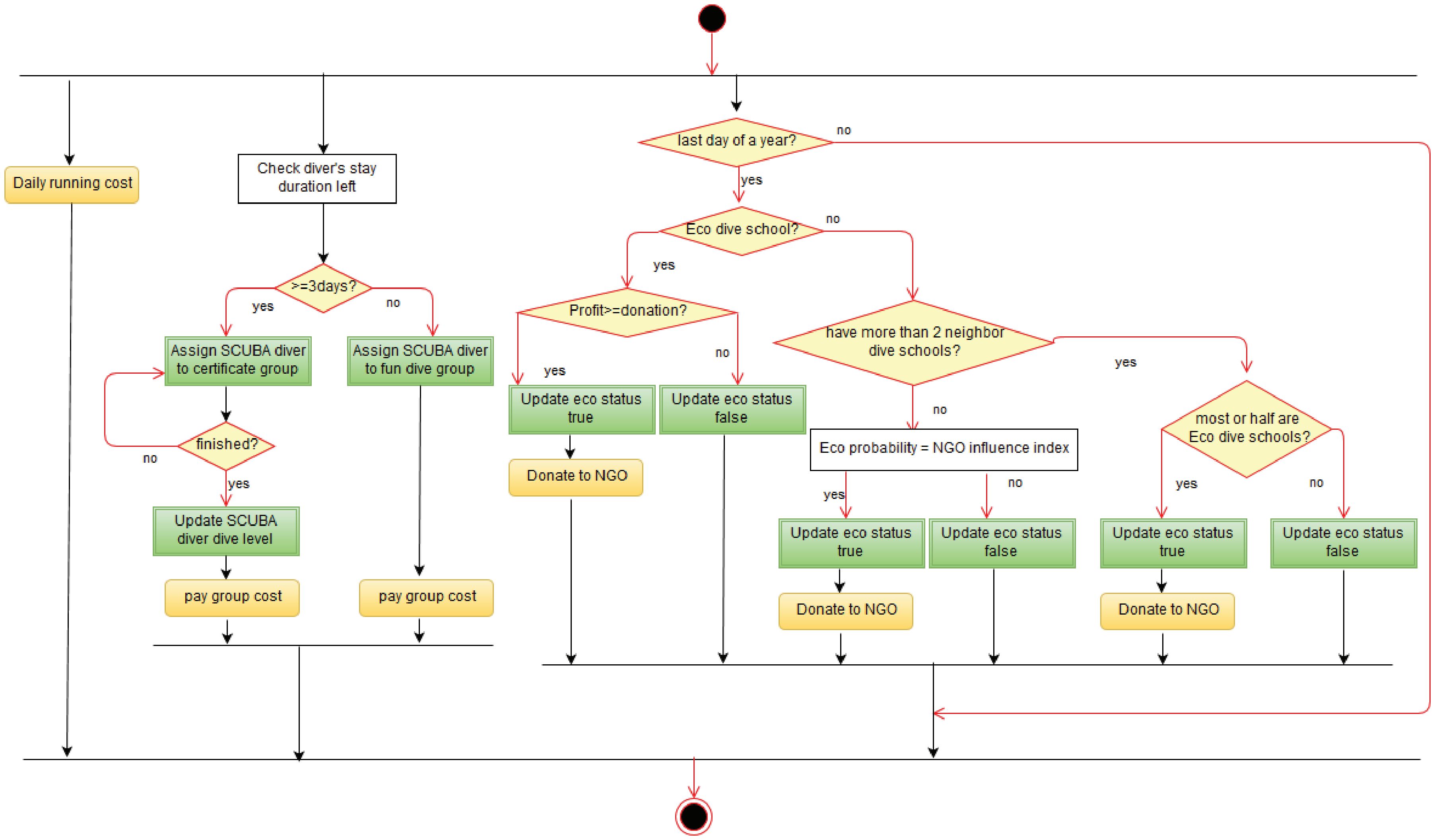


Figure 2.8: Activity diagram of dive schools.

Like the NGO, the financial flow of the dive schools is also simulated in KohTaoSim as a hashtable in JAVA. This ‘finance book’ contains details of incomes and outgoings, with their respective sources and recipients. Dive schools earn money from SCUBA divers. The prices of services offered (i.e. fun diving vs. certification courses) and dive group sizes differed among dive schools (Table 2.3). Eco-dive schools offered smaller group sizes and additional conservation tutorials, and charged correspondingly higher prices. The dive school finance book records this, indicating whether the fee is paid by an eco-diver or non-eco diver. In the model, there is a normal fee charged by all dive schools and also an additional fee charged to divers who register with an eco-dive school. The dive schools’ outgoings include running costs (materials, electricity, tax and equipment maintenance), incidental costs of dive courses (e.g. food for participants, payment for dive masters and/or instructors) and the transportation costs, which vary from boat to boat. In addition, dive school that apply for eco-labelling have to make a donation to cover the costs of the eco-labelling scheme and support other conservation activities by the NGO.

Table 2.3: Prices (Baht) and group sizes for services offered by dive schools, estimated from telephone interviews, observations made around the island and focus group meetings.

Type of course	Eco-dive school (n = 8)		Non-eco dive school (n = 47)	
	Mean	SD	Mean	SD
Certification course (price)	9513	252	8494	378
Fun dive (price)	1004	256	805	89
Certification course (size)	4	0.0	6.5	0.9
Fun dive (size)	7	0.9	8.5	0.9

Natural agent: Dive/snorkel sites

Coral reefs in this model are represented according to their use for SCUBA diving and/or as snorkelling sites, rather than as living organisms. Each dive site is defined by its name, map coordinates, distance from the coast, type (open-water SCUBA, advanced open-water SCUBA, snorkelling), and whether or not the site is affected by the monsoon (yes/no).This information is presented in Table 2.4.

Table 2.4: Dive site parameters and attributes. S: snorkelling site; O: open-water SCUBA dive site; A: advanced open-water SCUBA dive site. (Note: in the model, dive site names were entered without spaces between words.)

Name	Simulation environment map Coordinate X	Simulation environment map Coordinate Y	Distance to the coast (m)	Type	Influenced by monsoon ?
Ao Leuk	514	701	5	O	yes
Hin Ngan	523	743	5	S&O	yes
Ao Mae Haad	275	557	5	S	no
Shark Bay	424	784	20	S	yes

Laom Thian Pinnacle	691	496	20	O&A	yes
Ao Hin Wong	596	332	20	S&O	yes
Light House	570	103	20	S&O	yes
Mango Bay	448	114	20	S&O	yes
Sairee Reef	329	402	20	S	no
King Kong	604	672	30	O&A	yes
Japanese Garden	207	160	100	S&O	no
Twins	168	193	200	O&A	no
Green Rock	143	76	200	O	no
Nanyuan Pinnacle	203	101	300	A	no
Hin Wong Pinnacle	658	366	300	A	yes
White Rock	167	272	650	O	no
Sattakut	196	377	650	A	no
Shark Island	598	816	3000	A	yes
Chumpon Pinnacle	30	60	12300	A	no
Southwest Pinnacle	171	867	12500	A	no

An indicator (termed the coral health index) is used to illustrate how attractive the dive/snorkel site is to tourists. It positively correlated to the percentage of hard coral cover as well as to biodiversity. The site becomes less suitable for diving and snorkelling when the value of the coral health index falls below a certain level and also, at some sites, when the occurrence of the monsoon restricts its accessibility (Fig. 2.9). Since the location of a dive site influences the cost incurred by dive schools when organizing SCUBA diving activities, the actual locations of dive sites on Koh Tao were incorporated in the KohTaoSim model (Fig. 1.2).

In KohTaoSim, the health status of the coral dive site is updated at intervals of one day. The dynamic of a coral reef dive site is simulated and simplified as 2 major processes: growth and mortality. The slow growth of coral reef ecosystems is represented as an average improvement of coral reef health index per day using a standard logistic growth function. The mortality at dive sites is simulated as a constant decline of coral health at dive sites resulting from regionally uncontrollable background stresses (global climate change, ocean acidification etc.), and from the direct and indirect damage caused by tourism activities. Thus mortality and growth rate determined underlying changes in coral health. In addition two kinds of damage due to tourism are considered: direct damage caused by the activities of divers and snorkelers and indirect damage arising from infrastructure development to support tourism (Eq. 2). Indirect and direct damage by tourists are explained in more detail in the section ‘Effects of tourism on coral reefs’.

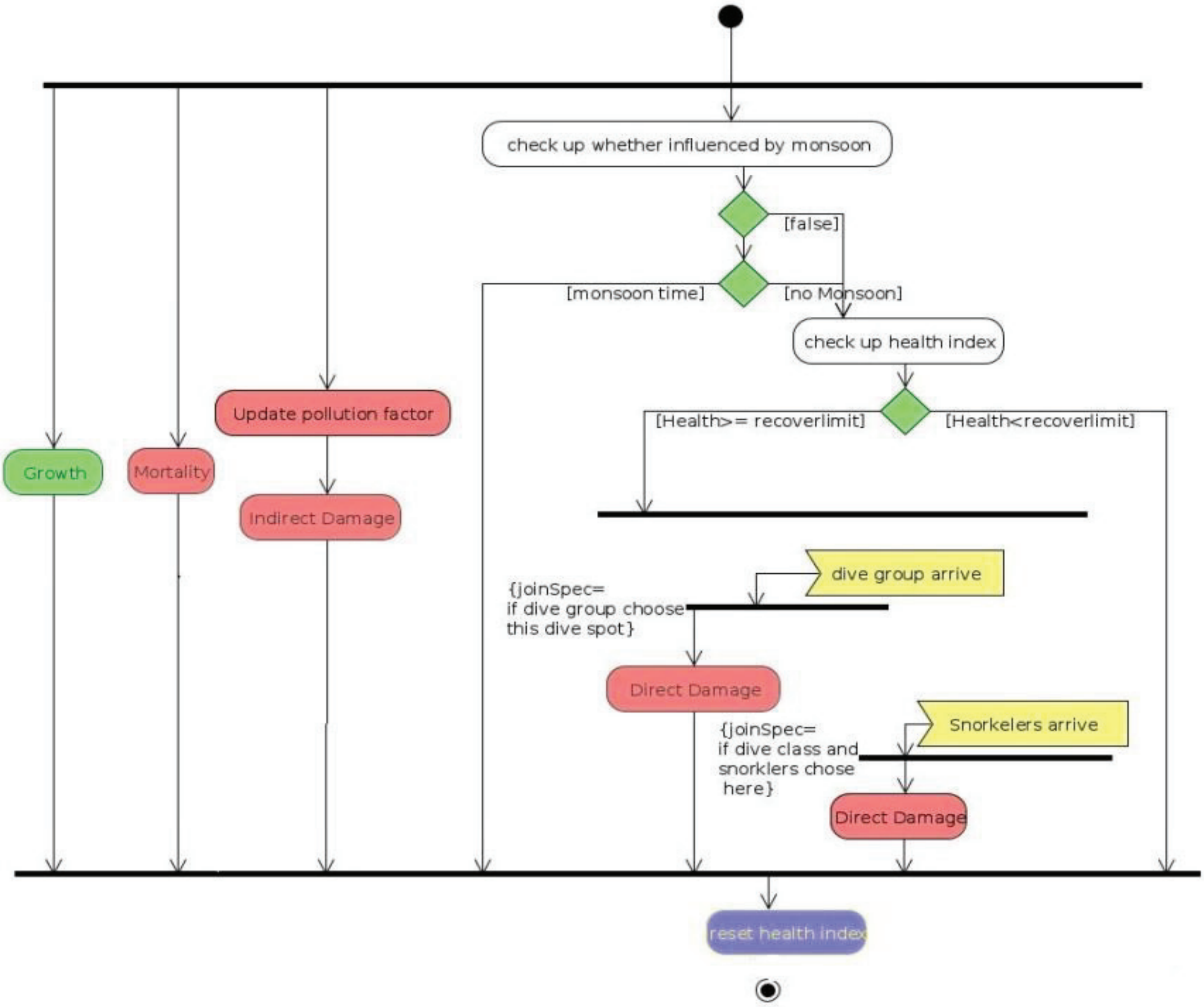


Figure 2.9: Flow diagram for updating health index of coral reef dive sites.

The coral health index is calculated as follows:

$$(2)\ H_t = H_{t-1} + \underset{\text{Growth}}{\boxed{H_{t-1} * G * \left(1 - \frac{H_{t-1}}{H_{\max}}\right)}} - \underset{\text{Mortality}}{\boxed{H_{t-1} * M}} - \underset{\text{Indirect Damage}}{\boxed{H_{t-1} * M * P_t}} - \underset{\text{Direct Damage}}{\boxed{Dd}}$$

H_t : Coral health index (0–100) at time t

$H_{\max}$: Maximum value of the coral health index (100)

G : Coral health index growth rate

M : Coral daily mortality

P_t : Pollution factor at time t (Eq. 4)

Dd: Direct damage (subtracted from the coral health index every time damage occurs)

2.4.3 Interactions and linkages

Effects of tourism on coral reefs

Indirect damage

In KohTaoSim, indirect damage simulates the indirect pressure of tourism on coral reefs, arising from the construction of tourism facilities and infrastructure (causing sedimentation) and the presence of more people on the island (causing increased sewage discharges). It is a statistical parameter indicating the relationship between coral mortality and the intensity of tourism measured as the overnight population (local residents plus overnight visitors). The parameter represents the impact of increased sewage discharges (which potentially reduce the rate of photosynthesis in corals, and lead to macro-algal overgrowth) among other negative impacts (Pastorok and Bilyard 1985). Since no direct data for Koh Tao is available, here I had to derive parameter values from data in the literature. However, there is still a knowledge gap in relation to this particular topic as, based on my literature review, few attempts have been made to establish a direct quantitative relation between coral mortality and population growth along the coast. This relation is usually described as involving complex processes and many influencing factors (Riegl et al. 2012). To simplify the model, I assumed that indirect damage to coral reefs is positively correlated to total overnight population on Koh Tao. Overnight visitor numbers have risen steadily since restrictions were relaxed in 1996. Comparison of the number of (officially registered) residents (Wongthong 2013) to daily tourist numbers (DMCR, 2010b) from 1992 till 2000, revealed a significant positive correlation ($r = 0.9719$, $n = 9$, $p = 1.2E\text{-}05$). If it is assumed that the ratio between numbers of tourists and local residents stays constant at the average value from 1996 to 2000 ($M = 4.59$, $n = 5$, $SD = 0.11$), the total overnight population of Koh Tao can be calculated as 1.22 times of daily number of overnight visitors. In the model, a threshold population number is included to represent the natural capacity of coral reefs to resist negative influences. When the overnight population exceeds this threshold, indirect damage occurs and thereafter increases proportionally to the growth in population (Eq. 3). During ground truthing stakeholders noted that the (negative) linear correlation between population and coral health exaggerated the negative impacts of population growth. In order to reduce the steepness of the correlation curve it was agreed that coral damage should be calculated as proportional to the square root of population growth, instead of as a linear correlation:

$$(3) \quad Di_t = \sqrt{\frac{(max.(T_t * 1.22, P_{thr}) - P_{thr})}{P_{thr}}} * D_i$$

I_t : Indirect damage at time step t

T_t : Tourist numbers at time t

$Pthr$: Threshold population number, i.e. the population below which no indirect damage is caused

Di : Indirect damage factor

Pollution factor

The dispersion of pollution effects from a source is usually a complex dynamic, which in marine environments is influenced by waves and currents, which determine rates of particle settling and vertical mixing processes (Larcombe and Woolfe 1999). In general, it has been proven that coral health increases with distance from sources of marine pollution, such as sewage outfalls (Pastorok and Bilyard 1985, Lapointe et al. 2011). The magnitude and spatial distribution of indirect damage originating from pollution is more important for KohTaoSim than the processes and mechanisms that give rise to this damage. As no data are available for Koh Tao, we draw on finding from the Makassar area in Indonesia, where a simple linear negative regression model has been used to describe the relation between the amount of sewage discharges and the distance of corals from the source of the pollution, with both values being log transformed (Risk and Erdmann 2000). Since there is no treatment of waste water treatment on Koh Tao, the model assumes that pollution decreases with increasing distance from the coast in a similar way, to a point beyond which no damage is caused. Thus, the actual damage experienced at a particular dive site is calculated as the pollution factor, based on the indirect damage factor calculated for the island as a whole (Eq. 3) and the distance from the coast of the dive site in question (Eq.4):

$$(4) \quad P_t = \left\{1 - \frac{\lg(L_x)}{\lg(D_{max})}\right\} * Di_t$$

P_t : Pollution factor, indirect damage rate at a dive site at time step t

I_t: Indirect damage at time step t (Eq. 3)

$D_{\max}$: Maximum distance from coast at which indirect damage is caused

L_x : The distance from dive site x to nearest coast line

Direct damage

Direct damage is caused by divers and snorkelers mainly through touching, trampling or breaking of coral fragments. Investigations show that direct damage by divers is related to the diver level, i.e. level of qualification (Thapa et al. 2006, Musa et al. 2011), the type of dive site and underwater camera usage (Barker and Roberts 2004, Chung et al. 2013). A similar opinion was expressed by participants in the focus group meetings with dive tourism stakeholders during the field work study on Koh Tao. Therefore, the model assumes that SCUBA divers who use underwater cameras to shoot pictures cause twice the damage of those without cameras. Other values for direct damage by SCUBA divers and snorkelers were calculated in relation to a standard damage factor D (the amount of damage caused by beginner divers at open-water sites, details see section 2.5.3 for the value of D) taking account of the depth of the site and the degree of experience of the divers, as described below. The depth of the site was assumed to determine the type of user. Deep sites were assumed to be inaccessible to snorkelers and beginner SCUBA divers; but shallow sites were also assumed to be of no interest to advanced SCUBA divers.

Snorkelling is possible at some open-water dive sites, but snorkelers cannot easily damage corals at these sites due to the depth. Therefore, the model assumes that snorkelers cause no damage at open-water dive sites. However, at pure snorkelling sites, snorkelers—who receive less training and environmental education than divers—are assumed to cause twice as much damage as SCUBA divers at open-water dive sites. At sites used by open-water and advanced SCUBA divers, the model further assumes that advanced SCUBA divers cause half the amount of damage compared to beginner (open-water) SCUBA divers. At advanced sites, the greater water depth makes it more difficult for SCUBA divers to cause direct damage to corals; therefore it is assumed that damage to advanced sites, by all SCUBA divers, is one-quarter the damage caused to open-water sites by beginner SCUBA divers. In some cases, skilled divers from eco-dive schools may also be involved in the coral restoration and protection program, which may lead to an improvement in coral health at some dive sites (Table 2.5).

Table 2.5: Direct damage caused by snorkelers and SCUBA divers at different types of dive sites, classified according to the type of user. D is the standard damage factor for SCUBA divers, based on the amount of damage caused by beginner (open-water) divers.

Type of dive site	Type of tourist	Damage
Snorkel	Snorkeler	D*2
Snorkel & open water	Snorkeler	0
	SCUBA diver	D
Open water	SCUBA diver	D
Open water & advanced	SCUBA diver beginner	D
	SCUBA diver advanced	D*0.5 (Eco-divers: -D)
Advanced dive site	SCUBA diver	D*0.25

Furthermore, regarding the damage caused by different types of SCUBA divers, several studies find limited underwater supervision (Barker and Roberts 2004) and high dive density (Hawkins et al. 1999) increase direct damage to coral during SCUBA diving. There was an overall consensus among respondents that eco-dive schools have smaller group sizes and better supervision. Thus the model assumes SCUBA divers dive with eco-dive schools cause half as much direct damage as divers of the same level at non-eco dive schools. Each and every visit by a snorkeler or SCUBA diver who arrives at a dive site is associated with a particular level of damage, which will impact on the coral health index calculated in the simulation (Fig. 2.9, Eq. 2).

Factors determining tourist numbers

It is commonly agreed that a healthy reef ecosystem is the main attraction of a coral reef based dive tourism destination, such as Koh Tao, for tourists (Flumerfelt 1999, Brickshawana 2003, Worachananant et al. 2008, Weterings 2011). Responses by tourists to my questionnaire showed that the reputation of Koh Tao can also be affected by visitor perceptions of overcrowding on Koh Tao, while SCUBA divers also took account of the cost of dive courses. Clearly there are some negative feedback processes involved: in particular, tourism activities have a negative influence on coral health, i.e. on the attractiveness of the island to tourists (Yeemin et al. 2006, Weterings 2011, Lamb et al. 2014). In this section, we explain how the interrelation between coral reefs and tourism is simulated by the model using equations developed based on the results of the field work.

Maximum daily tourist number

As evidenced in the tourist questionnaires, the average stay duration was determined as 5 days and the maximum capacity of the public ferry to Koh Tao is 480 tourists (arrivals) per 24 hours. Since both tourists and local businesses complain about overcrowding and low vacancies in infrastructures and accommodations, I consider that the island often operates near its carrying (i.e. accommodation) capacity currently, giving a maximum value of tourist numbers of 5 × 480 = 2400 ($T_{\max}$) that is used for following calculations.

Sightseer numbers

Sightseers' satisfaction and the reputation of Koh Tao are influenced by the visitor numbers on the island during their stay. The model assumes a delay in the dissemination of information among tourists throughout the world of approximately one year and computes the number of sightseers based on numbers a year (365 time steps) previously (Eq. 5):

$$(5)\ \ S_{max} = T_{max} * \alpha + T_{max} * \alpha * \beta \left(\frac{T_{t-365} - T_{max}}{T_{max}}\right)$$

$$if\, S_t > S_{max} \qquad then \quad S_t = S_t$$

$$if\, S_t < S_{max} \qquad then \quad S_t = S_{max}$$

S_t: Sightseer numbers on Koh Tao at time t

$S_{\max}$: Maximum expected sightseer numbers

$T_{\max}$: Estimated maximum daily tourist numbers

T_{t-365}: Tourist numbers at 365 time steps previously

α: Sightseer factor, i.e. the baseline percentage of sightseers among tourists

β: Crowd size influence factor, i.e. the percentage of sightseers who are influenced by how crowded Koh Tao is

Snorkeler numbers

In contrast to sightseers, snorkelers value the health of coral reefs, which determines Koh Tao's attractiveness and reputation among this group of tourists. Thus, its attractiveness is assumed to be correlated to the average of the health index of all diving/snorkelling sites 365 time steps earlier (Eq. 6):

$$(6)\ K_{max} = T_{max} * \omega\{1 + \left(\frac{H_{t-365} - HD_{max}}{HD_{max}}\right)\}$$

$$if\ K_t > K_{\max}\quad then\ K_t = K_t$$

$$if\ K_t < K_{max}\quad then\ K_t = K_{max}$$

K_t: Snorkeler number on Koh Tao at time t

$K_{\max}$: Maximal expected snorkeler number

$T_{\max}$: Estimated maximal daily tourist numbers

$HD_{t\text{–}365}$: Average coral health of all dive sites at previous 365 steps

$H_{\max}$: Maximal coral health index

ω : Snorkeler factor, i.e. the baseline percentage of snorkelers among tourists)

SCUBA diver numbers

For some SCUBA divers, especially those who come for fun dives, exploring healthy coral reefs is the main purpose of visiting Koh Tao. However, as it was mentioned, some of the SCUBA divers chose Koh Tao as an affordable place to get diving certificates. Thus, the number of SCUBA diver is only partially influenced by coral health (Eq. 7):

$$(7)\ M_{max} = T_{max} * \gamma\{1 + \delta * \left(\frac{H_{t-365} - HD_{max}}{H_{max}}\right)\}$$

$$if\ M_t > M_{\max}\qquad then\ M_t = M_t$$

$$if\ M_t < M_{max}\qquad then\ M_t = M_{max}$$

M_t : SCUBA diver number on Koh Tao at time t

$M_{\max}$: Maximum expected diver number

$T_{\max}$: Estimated maximum daily tourist numbers

$HD_{t\text{–}365}$: Average value of the coral health index of all dive sites at 365 time steps previously

$H_{\max}$: Maximum value of the coral health index

γ: SCUBA diver factor (the base line percentage of SCUBA diver factor among tourists)

δ: Coral health influence factor, i.e. percentage of SCUBA divers who come to explore coral reefs

Festival and monsoon season

At any given time, the total number of visitors on the island is the sum of sightseers, divers and snorkelers. This model adjusts this value to reflect the variation in overall attractiveness of the island at different times of the year. It is known that the total number of visitors on the island is approximately doubled during festival times and halved during monsoon season (Wongthong and Harvey 2014). The model simulates this phenomenon by adjusting the duration of stay of visitors to the island: visitors stay longer to experience the Koh Tao festival and leave early due to poor conditions on the island during the monsoon season.

Factors influencing selection of dive schools and dive sites

Tourist's eco-status

All the tourists are pre-defined as non-eco tourists by default. To acquire a high level of environmental awareness (and become eco-tourists) in this simulation, the following rules are applied, based on statistical analysis of answers to the questionnaires (see 'Tourists'): (1) Tourists can be pro-environmental before they come to Koh Tao. This simulates a pre-existing interest in conservation in their daily lives. The percentage of tourists who are pro-environmental (and thus eco-tourists) on arrival is called the 'pro-environmental rate'. Tourists may have received environmental education from NGO on Koh Tao, for example by seeing flyers or posters. The number who do so is dependent on the NGO influence index. Then these tourists make their own decision whether to become eco-tourists and support the NGO or not. The percentage of tourists who decide to become eco-tourists is called the free decision rate. After this number is calculated, randomly among all the tourists, this proportion of visitors who have received environmental education change their eco-status to 'eco' (Eq. 8 & Fig.2.10).

$$(8) \qquad T_t = S_t + K_t + M_t$$
$$T_{eco\_t} = T_t * P_{eco} + T_t * (1 - P_{eco}) * E_t * F$$

T_t: Total tourist number at time t

S_t: Sightseer numbers on Koh Tao at time t

K_t: Snorkeler number on Koh Tao at time t

M_t : SCUBA diver number on Koh Tao at time t

T_{eco_t}: Eco-tourists number at time t

P_{eco}: Pro_environmental rate

E_t : NGO influence index at time t

F: Free decision rate

Dive school's eco-status

According to our field work investigations, among the dive schools recorded in the study area in 2013, the majority (47) were non-eco schools; only 8 were eco-schools. Once per year, the local NGO *Save Koh Tao* announces the top pro-environmental dive school, taking account of financial contributions to the NGO or/and participation in conservation projects on Koh Tao. As described in the previous section on SCUBA dive schools, the motivation for eco-labelling is primarily economic. Thus decisions on whether or not to become an eco-dive school are taken each year based on profit expectations. This is incorporated in a decision rule for dive schools in the model: if the income from the eco-label (the sum of additional incomes of eco-dive schools) covers the cost of donation required to gain the eco-label, then the dive school remains as eco-dive school; when it is less, it opts out (Fig. 2.8). It is therefore assumed that all the dive schools in this simulation are profit oriented, not conservation oriented. Furthermore, it was observed in field work that the competition among businesses, especially neighbouring dive schools, is very high - since when tourists arrive on Koh Tao, they tend to choose a dive school by comparing those located close to their accommodation. To simulate such competition among businesses on the island, in the model, non-eco dive schools update their eco-status in accordance with that of neighbouring dive schools. When more than half of their neighbours are eco-dive schools, non-eco dive schools change their eco-status to 'eco', hoping to attract more customers; otherwise they maintain their 'non-eco' status. Non-eco dive schools with less than 3 neighbours are assumed to check the current NGO influence index. The probability of a dive school changing its eco-status to 'eco' is positively correlated to the NGO influence index.

SCUBA divers assign dive school

Tourist who responded to questionnaires were asked about their willingness to pay more for their SCUBA dive or snorkel activities in order to support conservation of corals around Koh Tao, and if this was related to their perceptions of the health status of corals at the island. There was a significant difference in the willingness to pay between respondents that had a higher awareness of environmental conservation organisations and/or activities and those without (Kruskal-Wallis, $\chi^2 = 8.297$, df = 1, p = 0.0040). Tourists who knew about conservation organisations were more likely to support environmental conservation (Fisher's test, $p < 0.001$) than those who were not. Survey results did not indicate a difference in willingness to pay for conservation among SCUBA divers, snorkelers and sightseers. More importantly, no significant differences in willingness to pay were found between SCUBA divers at different types of dive school (eco or non-eco dive schools). But there was a difference in motivating factors: Among different reasons for assign dive school (i.e. no idea or a friend is a dive master in chosen dive school), 17% of SCUBA divers chose their dive schools based on price considerations, while 7% chose their dive school because of the environmental education provided there.

Thus in KohTaoSim, some SCUBA divers will choose a cheaper dive school (i.e. a non-eco dive school, for prices see Table 2.3) with a probability of P_{cheap} (see Eq. 9). It is assumed that the higher the NGO influence index is, the more tourists will get involved into environmental education, thus the probability of SCUBA divers basing their choice of school on price is assumed to be linearly negatively correlated to the NGO influence index as shown in following equation.

$$(9) \qquad P_{\text{cheap}} = \theta * E_t + \mu$$

P_{cheap} : Probability of SCUBA divers choosing cheaper dive school

E_t : NGO influence index at time t

θ : Statistical constant parameter

μ: Statistical constant parameter

The rest of SCUBA divers will make their decision to assign a dive school based on their pro-environmental status: firstly, divers update their eco-status (Eq. 8), then the eco-divers (i.e. SCUBA divers who are eco-tourists) randomly choose one dive school from among eco-dive schools. Meanwhile, non-eco divers randomly choose a dive school from all dive schools. When this chosen dive school is an eco-dive school then the eco-status of these divers changes to eco-diver. This is realistic, since eco-dive schools offer ecology and conservation courses to all customers. We assume after these education programs, those divers will behave pro-environmentally, especially during SCUBA dives, when they will be better supervised that at non-eco dive schools (Fig. 2.10).

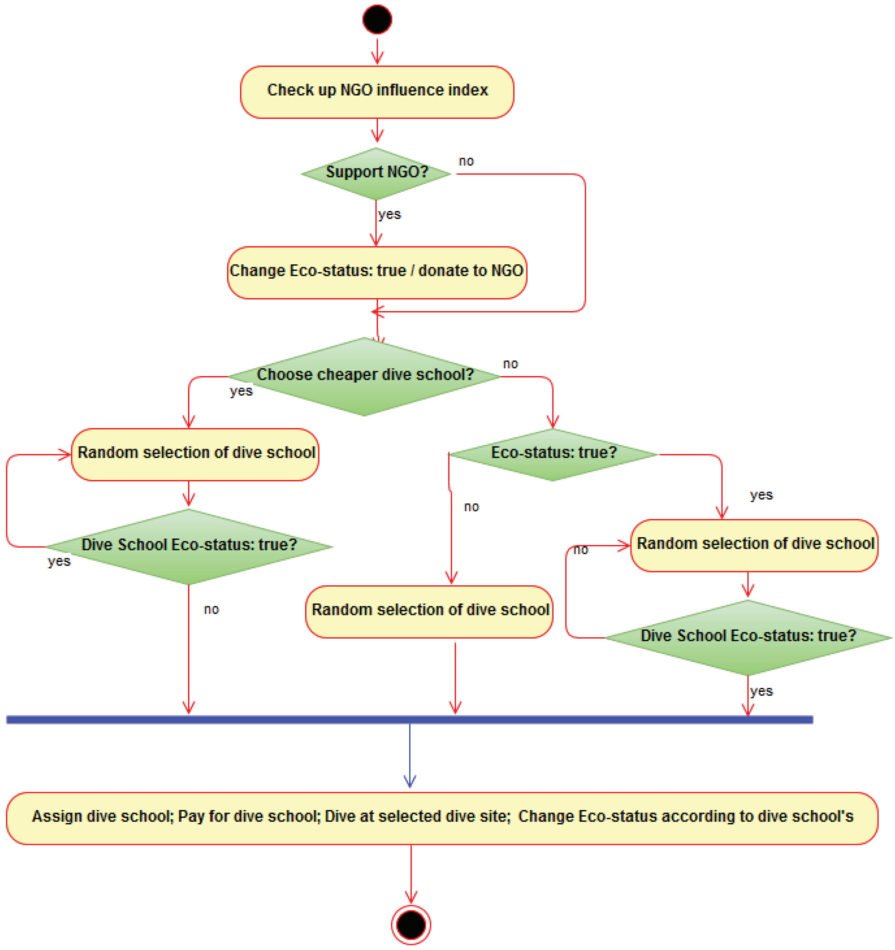


Figure 2.10: Decision making process: 'divers assign dive school'.

Dive school assigns dive site

Informants from eco-dive schools and non-eco dive schools described their decision making processes on dive site selection. Factors affecting the decision for a site included the status of coral reefs, the quality services provided to tourists, the need to regulate visitor numbers, the quality of infrastructure and, most importantly, visitor safety. Nearly all focus group participants agreed that their choice of dive site is also influenced by weather conditions, distance from the dive school and suitability for dive levels of the dive groups. In addition, all eco-dive masters and instructors prioritized selection of less crowded sites as this helps to reduce the stress on more popular coral reefs. By contrast the majority of the non-eco dive masters and instructors preferred to dive at sites with better coral health in order to satisfy SCUBA divers' expectations. The different preferences and behaviours of eco- and non-eco dive schools in selecting coral reef dive sites were incorporated into the simulation model. For simulating dive site selection, the model adopts the criteria used by dive schools as identified in the focus group meetings. Firstly, the dive sites are selected for safety reasons: according to current weather conditions and matching the dive depth and degree of difficulty the site presents to the skills of the divers. Secondly, dive schools try to make use of closer dive sites to reduce transport costs. Thirdly, eco-dive schools prefer less crowded sites to reduce stress on overused areas, while non-eco-dive schools prefer the most attractive dive sites with the healthiest corals (Fig. 2.11).

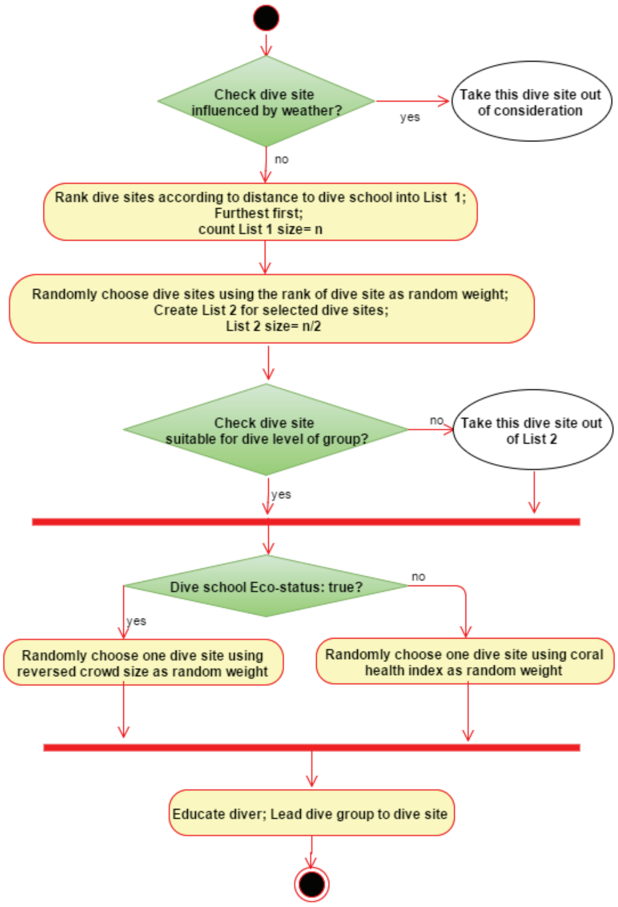


Figure 2.11: Decision making process: 'dive school assigns dive site'

2.4.4 Process overview

Initialization

In general, the model simulation follows a realistic and logical process, similar to what actually occurs on Koh Tao. Firstly, the simulation is initialized by creating all the necessary folders and elements of the working environment such as two-dimensional grid environment, dive sites, dive schools and tourists. From different resources we (author and local participants) defined the initial values of KohTaoSim as in Table 2.6:

Table 2.6: The initialization values of KohTaoSim

Variable	Initialized	Sources
Coral health index at all sites	100	Initial value
NGO influence index	0.2	Tourist questionnaire
Probability of choosing cheap dive school (P_{cheap} in Eq.9)	0.278	Tourist questionnaire
Number of eco-dive schools	3	Tourist questionnaire
No. of sightseers arriving per day (first year)	A random number between 17 to 27	Assumption based on tourist questionnaire
No. of snorkelers arriving per day (first year)	A random number between 100 to 190	Assumption based on tourist questionnaire
No. of SCUBA divers arriving per day (first year)	A random number between 100 to 190	Assumption based on tourist questionnaire

Scheduling

One simulation year is 365 days and one simulation day includes 2 time steps. The even numbered time step is defined as morning and the odd step is afternoon. The daily activities and their timetables are presented in Fig. 2.12. In deciding how different processes were to be scheduled, the main priority was to minimize computer memory use in order to reduce simulation time. Among the same class of agents, the scheduling sequences for actions are in a random order.

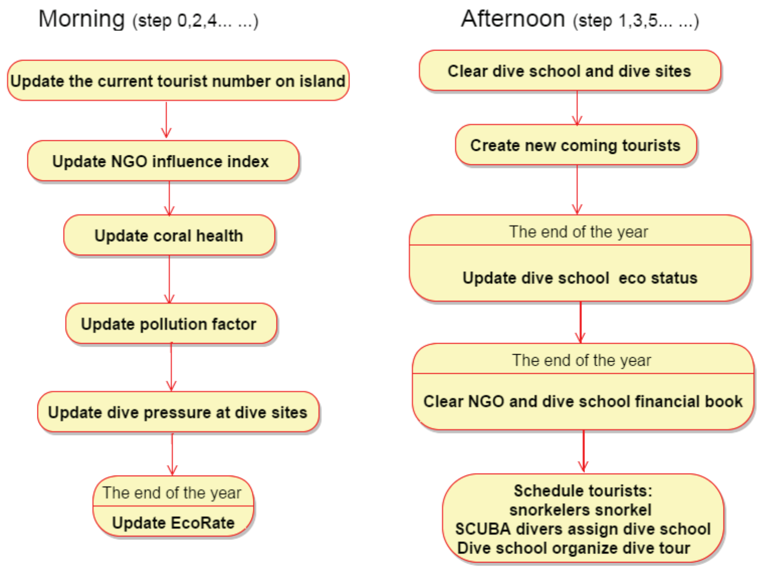


Figure 2.12: Sequences of KohTaoSim principal operations.

2.5 Model parameterization

The process of deciding and defining the parameters necessary for a model (the parameterization process) involves transformation of quantitative information from interviews, group discussions and role playing games into model inputs. Four principal types of parameterization were applied. The first type, direct input, was used when the variable could be directly introduced into the model as a parameter value. The second type of parameterization is indirect input of an estimated value, based on interpretation of empirical data from the tourism questionnaires. The third type is abstraction from secondary data. This was applied in this study mainly for ecological parameters. The fourth type involved refining and revising the parameter value through a series of sensitivity analyse with reference to an independent data set.

2.5.1 Direct inputs

A variety of methods was employed to collect the social and economic data, including semi-structured interviews with key informants, surveys administered to selected tourists, focus group discussions and role playing games with key informants, and observations made at various locations on Koh Tao. Direct input was used when this data could be directly introduced into the model as a parameter value. This included, for example, data on the NGO's financial situation and expenditure by tourists. Boundary conditions which were considered fixed for the situation under investigation were also introduced directly into the model (e.g. duration of monsoon season, dates of the Koh Tao festival (for simplicity reason, it is simulated as fixed date), and geographical information on dive sites and dive schools). The values and respective sources of information are presented in Table 2.7:

Table 2.7: Values of direct input parameters in KohTaoSim, and the source of information for each parameter. KI: key informant interview; RPG: role playing game; I&R: key informant interviews and confirmed by role playing games; TI: telephone interview; SD: confirmed by secondary data (DMCR, 2010b); TQ: tourist questionnaire.

Parameter	**Value**	**Source**
Beginning of monsoon season	First day in Nov.	KI
End of monsoon season	Last day of Dec.	KI
Beginning of Koh Tao festival	13th of April	KI
End of Koh Tao festival	15th of April	KI
Beginning of weather limitation (east side of Koh Tao)	Last day of Oct	KI
End of weather limitation (east side of Koh Tao)	Last day of March	KI
Group size for fun dive group at non-eco dive school	20	RPG & KI
Group size for fun dive group at eco-dive school	10	RPG & KI
Group size for certification dive group at non-eco dive school	4	RPG & KI
Group size for certification dive group at eco-dive school	8	RPG & KI
Maximum effectiveness level of NGO funding ($F_{\max}$ in Eq. 1)	75000000	I&R
Minimal donation from dive school to NGO	160000	I&R
Festival donation from tourists to NGO	1000	I&R
Fund from government to NGO	1000000	I&R
Basic daily running cost of dive school	-2500	I&R
Maintenances cost per SCUBA group	-500	I&R
Transportation cost for SCUBA trip (per metre distance between dive school and dive site)	-0.25	I&R
School income from certification course in non-eco dive school	4000	TI
Extra school income from certification courser for eco-dive school	1000	TI
School income from a fun dive group in non-eco dive school	800	TI
Extra school income from a fun dive group for eco-dive school	200	TI
Coral health influence factor for SCUBA diver (δ in Eq. 7)	0.47	TQ
Crowd size influence factor (β in Eq. 5)	0.5	TQ
Sightseer factor (α in Eq. 5)	0.17	TQ & SD
Snorkeler factor (ω in Eq. 6)	0.415	TQ & SD

SCUBA diver factor (γ in Eq. 7)	0.415	TQ & SD

2.5.2 Indirect inputs

Indirect input (Table 2.8) was applied to descriptive information, relating to the qualification level of divers, underwater camera usage and duration of stay on Koh Tao by different types of tourists. Values were assigned based on interpretation of the empirical data from responses to the tourism questionnaires. In the cases of stay duration, values were assigned randomly based on the distributions for different classes of visitor shown in Figure 2.7.

Table 2.8: Values of indirect input parameters in KohTaoSim. In all cases the source of information was responses to tourist questionnaires.

Parameter	Value
Beginner diver rate (% among all SCUBA divers)	0.5
With underwater camera rate (% among all SCUBA divers)	0.36
Pro-environmental rate (% among tourists, $\boldsymbol{P_{eco} in\ Eq.8}$)	19
Free decision rate (% among divers, F in Eq.8)	71
Stay duration	Values see data presented in Fig. 2.7

2.5.3 Parameters estimated from secondary data

Ecological parameters

Although there are a number of coral-related ecological data sets available for Koh Tao (Table 2.9), knowledge of the ecological status of corals is still deficient, due to the difficulty of comparing data sets compiled using different standards, methods and indicators. In the model, ecological parameters are mainly based on the longest available secondary dataset, compiled by the Thai government's Department of Marine and Costal Resources (DMCR 2010a & 2010b; Appendices 3.1, 3.2 &3.3); and, additionally, on expert knowledge of local coral ecologists. In cases where discrepancies among data sets were found, the value of the ecological parameter concerned was later double-checked by applying model sensitivity analysis and comparison with Reef Check data combined with EMP data for Koh Tao (details see section sensitivity analysis).

Table 2.9: Three sources of ecological data on the health of Koh Tao corals. The three data sets are(were) compiled using different standards and methods. DMCR: the Department of Marine and Costal Resources of Thailand

Data base	**Time scale**	**Sampling frequency**	**Author or institution**	**Standard or method**
Save Koh Tao (EMP)	2006 till present	Every 3months	Chat Scott	Line intercept technique
Eco Koh Tao (Reefcheck)	2008 till 2011	Every 3 months	Nathan Cook	Reef Check

DMCR	1989 till present	Every 3 years	DMCR	Manta tow technique

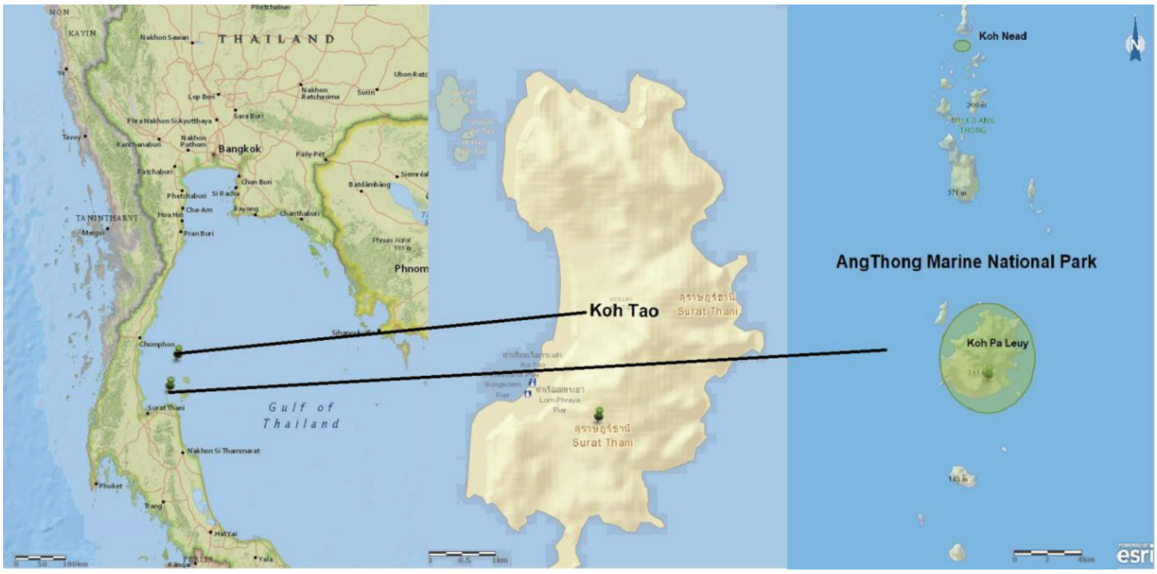


Figure 2.13: Koh Tao and Ang Thong National Marine Park (insets) and their locations in the Gulf of Thailand. Source: Arcgis (https://www.arcgis.com/home/webmap/viewer.html).

For a deeper understanding of the influence of dive tourism on coral ecosystems, a tourism restricted area, Ang Thong Marine National Park (MNP), was selected as a baseline for KohTaoSim parameterization. This MNP is also located in the Gulf of Thailand, only 30 km from Koh Tao and 16 km from the Thai mainland (Fig. 2.13). It was established in November 1980, and covers a marine area of over 100 km² containing 42 islands. Since 2002, this marine park has been partly open for tourism activities on payment of a 1500 Baht (35 Euro) entry fee, but registration is required for all activities undertaken in the MNP (Sethapun 2000). In general, the health of coral at Ang Thong is not as good as at Koh Tao, mainly because Ang Thong is located close to mouths of rivers in the Surat Thani area, and acts as a barrier intercepting most sediments and pollution from this source before they reach at Koh Tao (information from key informant interviews with local ecologists). However, the same pattern of long-term decline in coral health can be seen in officially documented ecological data for both sites (Table 2.10). Among these 42 islands in the Ang Thong MNP, Koh Pa Luey is the only inhabited one. This island has been developed for tourism (resorts and hotels). By contrast Koh Nead has been designated an intangible (no-take) area within the MNP. Despite attempts by the Marine National Park Division (MNPD) to restrict the number of overnight stays (Sethapun 2000), a 4-day trip to Ang Thong MNP including camping (or hotel), kayaking, and snorkelling has become more and more popular over the last decade (TAT 2014).

Table 2.10: Long-term monitoring data for Koh Tao and Ang Thong Marine National Park, based on official government statistics, published in Thai (Appendix 3.1 & 3.2) and unpublished coral surveys undertaken in 2011 (Appendix 3.3). LC: live coral cover, DC: dead coral cover.

	Koh Tao		Ang Thong (Ko Pha Luey)	
Year	LC:DC	Status	LC:DC	Status
1988	86.814	Very good	14.29	Very good
1989	6.034	Very good	10.54	Very good
1991	3.06	Good		
1995-1997	3.39	Good	3.44	Good
1999	1.11	Fair	2.17	Good
2006	1	Fair		
2009	1	Fair		
2011	0.8	Fair	0.3	Bad

Coral health index growth rate (*G* in Eq. 2)

Tanote Bay in Koh Tao was used as a reference site to estimate average reef health index growth rates because a heavy rain event in 2008 caused damage to a dam, releasing large amounts of sedimentation into the bay and burying all corals in the bay. Since then, coral recovery has commenced at this location with 3 species dominating, averaging 0.005% growth per day in the extent of live coral cover (expert knowledge, confirmed by unpublished data collected by the EMP on Koh Tao). Since there is no direct discharge of waste water in this bay, the data provides a reference value for coral growth in the absence of direct pollution and sedimentation. However, for simulation of recovery of biodiversity in the model, a slightly lower value of *G* was used (0.00375% per day), that agreed with estimations of 15 years as the time needed for recovery of the coral reef community at Koh Tao by local coral experts in key informant interviews.

Coral mortality (*M* in Eq. 2)

The mortality rate of coral was parameterized by setting both direct and indirect damage as 0 in the simulation. The coral health index remains around 92 i.e. the average hard coral coverage of all coral reefs around KohTao in the year 1988 (DMCR 2010a), and to achieve this mortality was calculated as 0.0003% per day.

Direct damage factor (*Dd* in Eq.2)

It is widely documented that SCUBA divers cause physical damage to corals as a result of direct contact with fragile organisms (Zainal Abidin and Mohamed 2014). Evidence shows that such direct damage is more significant in heavily-dived sites compared to sites where diving pressure is lower (Hawkins and Roberts 1999, Barker and Roberts 2004). However, there is limited data available on damage to corals by divers at Koh Tao. I used data from a published study of damage by divers at Koh Tao, and data on coral cover at one high-use dive site (Twins) and one low-use dive site (Mango Bay), to calculate estimate the direct damage factor (*Dd*) for the two sites (Table 2.11). By averaging these two values the estimated value *Dd* for the island as a whole was calculated to be 4.4E-05(reduction of coral health index per dive, in Eq.2). Table 2.11 Indicators of coral damage and dive pressure at high and low-use dive sites at Koh Tao. Data on physical damage to corals at Koh Tao is based on a survey of 4516 and 5983 colonies with low and high levels of use, respectively (Lamb et al. 2014). The number of divers per site was calculated based on estimates of the total number dives made at Koh Tao, and published data on the distribution of dive site usage frequency (Weterings 2011). A total of 60,000 dive certificates were issued on Koh Tao in 2011 and each dive certificate represents 4 dives on average (Wongthong and Harvey 2014). Responses to my tourism questionnaires indicated that the ratio between fun divers and divers seeking certification is 1:1; furthermore each fun diver makes on average 2 dives, known from tourists questionnaire. Thus the total number of dives made at Koh Tao in 2012 was estimated to be 360,000. (60,000*4+60,000*2=360,000 dives).

Table 2.11: Indicators of coral damage and dive pressure at high and low-use dive sites at Koh Tao. HCC: hard coral cover at dive sites Twins (high use) and Mango Bay (low use) in 2011 (unpublished EMP data); PD: percentage of coral colonies with physical damage at Koh Tao at sites with low and high levels of use (Lamb et al. 2014); DP: dive pressure, i.e. estimated number of divers each year at Twins and Mango Bay. Dd: direct damage factor at Twins and Mango Bay, i.e. the estimated percentage of physically damaged hard coral cover per dive ($\mathrm{Dd} = \frac{\mathrm{HCC}*\mathrm{PD}}{\mathrm{DP}}$).

Type of site	HCC (%)	PD (%)	DP (no. of dives per year)	*Dd* (%)
High use	53.65	12.4	105,171	6.32551E-05
Low use	41.66	0.98	16,670	2.44918E-05

Indirect damage factor (***Di*** in Eq. 3)

Indirect damage in KohTaoSim is a parameter used to simulate how coral mortality can be influenced by tourism development, using visitor numbers as an indicator. Calculation of the parameter is based on ecological data from a protected area near Koh Tao, i.e. Ang Thong MNP (Fig. 2.13). Within the MNP, Koh Pa Luey is the only inhabited island and also the only one with facilities for tourists, including a pier which is used as an embarkation point for recreational activities around other islands. In 1998, the island had a resident population of 527 and received 54,323 visitors (Yeemin 2005), who were not allow to stay overnight (Sethapun 2000). By 2012, the number of residents had increased to approximately 850 (key informant interview with DMCR). In this year 102,996 tourists visited the island (Sethapun 2013). These were mainly participants in 4-day package tours to Ang Thong MNP (in TAT, 2014), even though, officially, overnight tourism was still prohibited. Assuming that all visitors stayed for 4 days the number of visitors on the island each day can be calculated at 102,996 × 4/365 = 1129. Thus, the daily population of Koh Pa Leuy (including tourists who stay overnight and local residents) increased 3.7 fold in the period between 1998 and 2012. Meanwhile, the health of coral reefs around Koh Pa Leuy has deteriorated dramatically, from

55% healthy coral cover at the start of the century (Yeemin 2005) — which can be considered reasonably good, given the exposure of island to sediment and pollution from the nearby coastal zone — to roughly 20% now. By contrast, Koh Nead, a small island in the intangible zone of AMNP, lost no more than 5% of its healthy coral cover between 1998 and 2012 (key informant interview with a local ecologist and DMCR monitoring data; Appendices 3.1 & 3.3). In calculating the parameter I made the following assumptions: (1) since historical records indicate that coral heath was good till 1999, the oldest available value for the number of residents (527) can be considered as the population threshold (*Pthr* in Eq. 3) for Koh Pa Leuy . (2) In comparison with Koh Nead, Koh Pa Leuy has suffered approximately 7 times the amount of coral loss. This increased coral loss is assumed to be due to indirect damage associated with the growth in population numbers. Putting these values into Eq. 3, the estimated indirect damage factor value is 4.2.

Maximum distance from coast at which indirect damage is caused (Dmax in Eq. 4)

According to monitoring data from the DMCR (2010a), the coral health of Chumphon Pinnacle and the Southeast Pinnacle (the 2 furthest dive sites around Koh Tao) are not influenced by the rapid growth of dive tourism. These 2 sites are approximately 13 km from the Koh Tao coastline. Therefore, I defined the maximum distance from coast where indirect damage is caused as 13,000 m.

Social-economic parameters

Threshold population number (*Pthr* in Eq. 3)

The threshold population number is the maximum overnight population that will not cause any detectable indirect damage to coral. A very clear decrease in the ratio of live coral to dead coral from 86.8 to 6 at Koh Tao (Appendix 3.1) can be seen between 1988 and 1989. This may partly be due to the 1988 coral bleaching event in the Gulf of Thailand. However, the coral health status has never recovered to the pre-1988 level (DMCR 2010a; Appendix 3). Thus I estimated the threshold population number is as 650, representing the original indigenous population of less than 350 persons (key informant interview with local Thai families) and 300 tourists (according to historical records of room occupancy in tourist accommodation; Wongthong 2013).

Statistical parameters (θ and μ in Eq. 8)

At the moment, the NGO influence index (E_t in Eq. 8) is around 0.1 (from key informant interviews), while the probability of choosing a cheap dive school (P_{cheap} in Eq. 8) is 0.278 (responses tourist questionnaire, where 27.8% of respondents indicated that ‘low price’ was the most important consideration in choosing a dive school). Logically, when the NGO influence index is 1.0, the probability of choosing cheap dive school is 0. By knowing these 2 points on this line the statistical parameters θ and μ can be calculated as $\theta = -0.31$ and $\mu = 0.31$.

2.5.4 Sensitivity analysis

In developing an ABM to simulate real-world phenomena, researchers need to know that changes in model inputs affect model outputs in ways that actually mimic real-life processes. The exploration of the influence of varying input values on the simulation outputs is referred to as sensitivity analysis (SA) (Frey and Patil 2002). Focusing on key influential parameters and processes, SA identifies uncertain parameter values and helps selects value that generate outputs compatible with empirical data (Schmolke et al. 2010). In this section, I explain how uncertain parameter values in KohTaoSim were detected, investigated, tested and re-defined through local SA (one parameter change at a time) and global SA (parameter combinations changes at a time), and revised in accordance with available empirical data (Thiele et al. 2014).

Uncertainty ranking for parameter

During the second period of empirical field work in Thailand and in the subsequent analysis process, the confidence level of all parameter values were evaluated and given a score (on a range of 0 to 10, where 10 is sure, 0 is no data available). Uncertain parameters were identified by me in consultation with local stakeholders. Parameters that scored less than 5 included the indirect damage factor (*Di* in Eq. 3), the direct damage factor (*Dd* in Eq. 2) and threshold population number (*Pthr* in Eq. 3). The main reason for lack of confidence in these parameters is that they relate to ecological processes that are not well understood by non-ecological stakeholders; moreover available empirical data consists of short time series that are only partially compatible with each other.

Local sensitivity analysis

The aim of single variable sensitivity analysis is identify parameters where additional research is required to strengthen the knowledge base, thereby reducing output uncertainty. In these tests, the 3 uncertain parameter values were increased and decreased 10% in total to measure the effect on the outputs (Table 2.12). The tests were run using the standard configuration, where simulation lasts for 25 years, with all remaining parameter settings set at values shown in Tables 2.6, 2.7 & 2.8. Also, the simulations were repeated 20 times with different random seeds for each parameter to allow for stochastic effects.

Table 2.12: Sensitivity analysis parameters and their testing values

Parameter	Configuration value	Variation range (±10%)
Direct damage factor (*Dd*)	4.4E-05	1.1E-06
Indirect damage rate (*Di*)	4.2	0.105
Threshold population number (*Pthr*)	650	16.25

Direct damage

By varying the value of the direct damage factor (*Dd*), the direct influence of SCUBA divers and snorkelers on coral health during the dive activity changes. Figure A4.1 (App. 4) presents the effects of direct damage factor input value changes on coral health. The snorkelling site is more influenced by direct damage than all types of dive site. However, even at the snorkelling site, the coral health index varies by no more than 1.6% with a ±10% variation in the value of the *Dd*. Also, there was not obvious change in tourist numbers and the income of dive schools. Thus this parameter was defined as non-sensitive and not included in further sensitivity analyses. It worth to explain that the dive sites used for both open water and snorkelling (O&S) seems to be not influenced by *Dd* because they are occupied by snorkelers and therefore not often chosen by dive schools and additionally less influential from indirect damage due to the distance from coast is further than snorkelling site. Furthermore, those sites are subject to relatively high levels of indirect damage from tourism, reducing coral health relative to open water (O) and advanced/open water (A&O) dive sites; thus they are also mostly shunned by non-eco dive schools.

Indirect damage

The model reacted relatively sensitively to variation in the value of the indirect damage factor (*Di*). Decreasing (increasing) this factor by 10% led to a 6.7% increase (6.6% decrease) in the coral health index (H_t) of nearshore dive sites. On average, a 10% increase (decrease) in the value of *Di* leads to a –3.4% (+4.6%) change in coral health index values (n = 20, Fig. 2.14). The indirect damage factor has a greater influence on coral health the nearer the dive site is to the shore (Eq. 4). Changed values of the coral health index lead in turn to dynamical changes in dive school income (Fig. A4.2) and tourist numbers (Fig. A4.3). Since divers are more concerned about coral health than general sightseers, changed indirect damage factor values have a greater effect on diver numbers than on sightseer numbers. In summary, the indirect damage factor is both uncertain and moderately sensitive, requiring further testing to define an appropriate value.

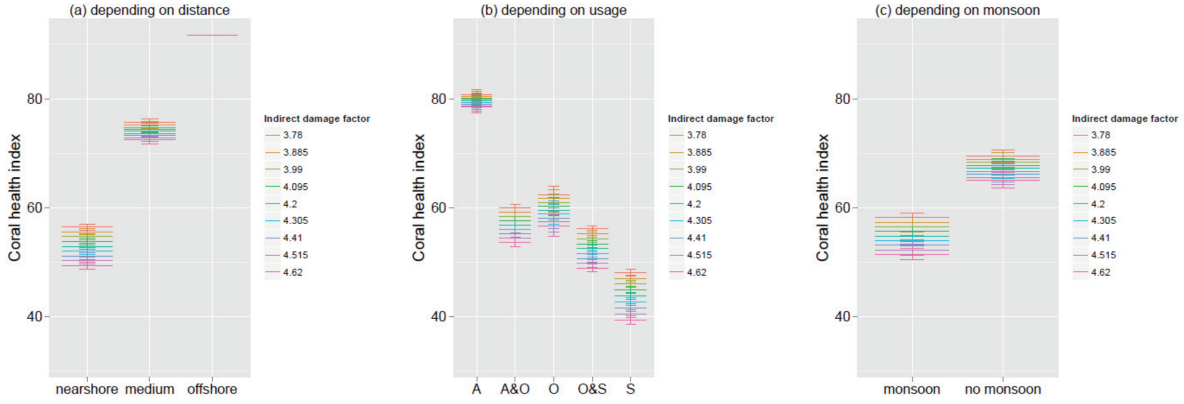


Figure 2.14: Changes in coral health index (H_t) values in response to changes (by up to ±10% in steps of 2.5%) in the value of the indirect damage factor (*Di*): (a) dive sites grouped according to distance to coast as nearshore, medium and offshore; (b) dive sites grouped according to the dive type as advanced SCUBA dive site (A), advanced and open water SCUBA dive site (A&O), open water SCUBA dive site (O), open water SCUBA dive site and snorkelling site (O&S) and snorkelling site (S); (c) dive sites grouped according to whether they are influenced in monsoon season; (d) all dive sites ranked according to their distance from the coast.

Population threshold

Sensitivity analysis revealed that the population threshold factor (*Pthr*) has a strong influence on coral health index (Fig. A4.4), dive school income (Fig.A4.5) and tourist numbers (Fig. A4.6). The coral health index showed a maximum variation of 4.6% at the dive site AoHaeMaad, and an average 3.3% variation from the configuration simulation value. The variation in the coral health index had discernable knock-on effects on tourist numbers and dive school income. Therefore, this parameter was also considered for further tests.

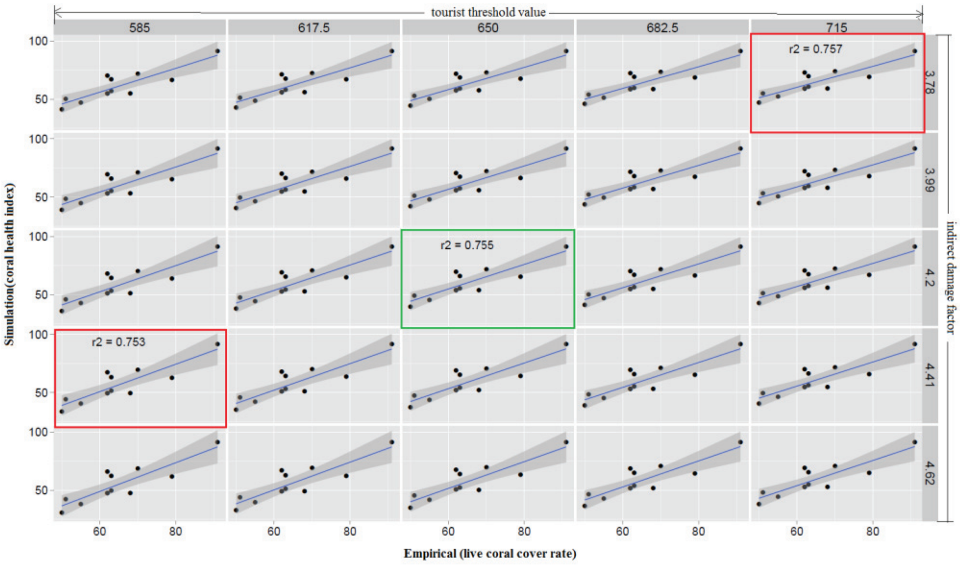
Global sensitivity analysis

Global sensitivity analysis is a method to minimize uncertainty in model outputs where uncertainties exist with regards to model inputs (Sobol and Sergei 2005). To conduct global SA I systematically looked at the entire range of values of parameters *Di* and *Pthr* identified as sensitive by single parameter SA. The combined value sets were further tested to assess the degree of fit with an empirical ecological data set, developed by combining data on live coral cover from Reef Check and EMP data bases. This limited data set contained data for only 9 different dive sites, which were used to provide empirical values for comparison with model values. Scatter plots were employed to analyse the results; qualitative differences between model output and empirical data were virtualized and the magnitudes of the resulting quantitative differences were estimated using Pearson's correlation. For reasons of clarity, every second plots are presented in Fig.2.15. The reason for choosing Pearson's correlation as an indicator of fit between the simulation results and the empirical data set, rather than regression or minimal deviation, is that the coral health index in this study is an index devised to indicate the attractiveness of a dive site (i.e. as positively correlated to hard coral cover and combined with bio-diversity at the site). By contrast the empirical data values are based on ecological monitoring of the extent of reef cover, which is a purely ecological concept. Thus, for the purposes of the model, capturing the tendency or general spatial pattern of coral health distribution is more important than obtaining the (statistically) best fit to empirical data.

As shown in Fig.2.15(a), the results of global SA suggest that in general terms, KohTaoSim is able to adequately capture the spatial pattern of coral health on Koh Tao (average $r^2(81) = 0.755$, SD = 0.0023). The combination of *Pthr* = 715 and *Di* = 3.78 yields the best correlation to the empirical data (average $r^2(9) = 0.757$, p = 0.01819). The combination of *Pthr* = 585 and *Di* = 4.41 yields the worst correlation to the empirical data (average $r^2(9) = 0.753$, p = 0.019178). However, the difference between the best or worst fitting correlation values is very small, as well as the fitting is very reasonable comparing with the original data calculated from the available knowledge, thus I continued to use my initial 'best guess' configuration values of these parameters.

Fig.2.15(b) gives a closer look at the scatter plot for the combination of *Pthr* = 650 and *Di* = 4.2 (configuration values). The dive sites 'Nanyuan Pinnacle' and 'Green Rock' are shown as lying outside the ±1 SE correlation range (grey shaded area), as the simulation result is significantly higher than the empirical data. The reason may be that, in contravention of regulations, one hotel and a few beach restaurants and clubs are still located on Nanyuan Island, in whose waters Nanyuan Pinnacle and Green Rock are located. This indirect pollution source is not considered in the simulation because of the lack of detailed knowledge of waste water discharges around Koh Tao. At the 'Mongo Bay' dive site, the simulated coral health index value is significantly lower than the corresponding ecological data. This may be because half the bay is cordoned off for exclusive use by guests of a hotel (author's personal observation). This restriction on access, not considered in the simulation, may be the reason why empirical data indicates that coral is healthier than in the simulation. For the sake of simplicity, uncommon and site-specific factors such as these are not incorporated into the model.

(a) Parameter value combinations of tourist threshold and indirect damage factor



(b) configuration value combination of tourist threshold(650) and indirect damage factor(4.2)

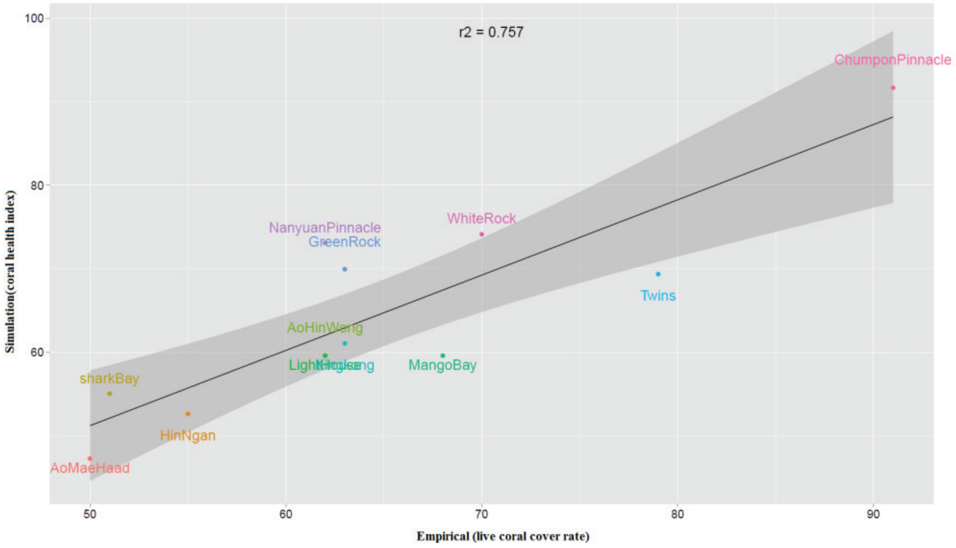


Figure 2.15: Global sensitivity analysis results: (a) Correlations between simulated (coral health index Ht) and empirical data (live coral cover rate) for different combined values of the indirect damage factor Di and the tourist threshold Pthr. The grey shaded indicates ±1 SE values. The green outlined square shows the correlation for the configuration values; red outlined squares show the best and worst fitting values. (b) Detailed data for the configuration values, i.e. the green outlined square in (a

2.6 Model validation

There have been many discussions about approaches for ABM validation in the past (e.g. Klügl 2008, Cooley and Solano 2011). The most commonly used method involves comparisons between independent data and model results. However, simple application of this approach does not adapt well to KohTaoSim for 2 main reasons: (1) for this location, historical data are only partly available and (2) KohTaoSim operates on different hierarchical levels synchronously. Thus a plain comparison of data congruity on the result levels might leave too many questions unaddressed (Klügl 2008, Kubicek et al. 2015). Therefore, I combined different validation methods: technical verification, visual inspection, statistical comparison, opinions of local experts, aggregation of data on higher integration levels and role playing games with stakeholders on Koh Tao, as set out by Kubicek et al. (2015).

2.6.1 Technical verification

Three steps of model verification were undertaken to confirm from a programming point of view that KohTaoSim behaved as planned and designed. Firstly, every code line was examined to confirm its function and correctness; Secondly, parameters were given extreme values to test boundary situations and capture exceptions or mathematical errors. Finally, simplified small test models with only few agents were tested, which enabled a closer look at the behaviour of each agent to confirm its correctness.

2.6.2 Statistical validation with independent data

ABMs normally have a hierarchical structure, where behaviour of single agents gives rise to the emerging properties of the model in the upper hierarchical level (Glaser 2012). Therefore, the validation of individual agents' rules, parameters and algorithms also requires checking their influence on higher integration levels. This principle was applied in testing how the chain of actions by dive schools and their interactions with other dive schools led to assignation of dive sites (Fig. 2.11). I validated this part of KohTaoSim by comparing the accumulated SCUBA diver numbers over the entire 25 years of simulation time with standard parameter settings to independent empirical data. Empirical data on the dive pressure was abstracted from GIS map of KohTao (Weterings 2011). In Weterings' study, he logged the actual usage of dive sites based on dive location announcements by dive schools on KohTao, which showed how often the different dive sites were chosen. The corresponding simulation results were obtained by logging how many SCUBA divers conducted SCUBA dive activities at each dive site during the simulation run over 25 years. Comparison of simulated and empirical data reveals a highly significant correlation ($r^2 = 0.898$, $p < 0.0001$; Fig. 2.14). Thus the decision making process by dive schools in the model leads to a selection of dive sites that adequately captures the reality.

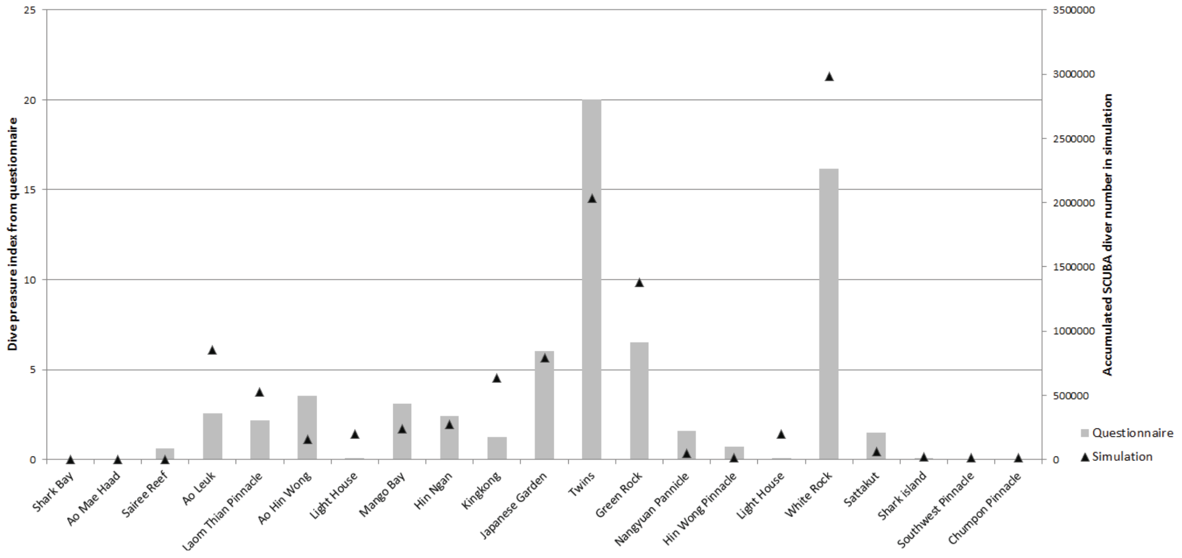


Figure 2.16: Comparison of simulated and empirical secondary data results for dive pressure at all sites. Simulation results are the accumulated SCUBA diver numbers during the 25 years the simulation was run. The empirical data and dive pressure index is based on answers to announcements of dive sites by the dive schools on how often the different dive sites were chosen (Weterings 2011).

2.6.3 Non-statistical validation by ground truthing

For evaluation of the behaviour of KohTaoSim as a whole (i.e. to assess whether it adequately reflects the real situation on KohTao), a ground truthing process was used. This involved participative role playing games and follow-up email correspondence with local coral experts (coral ecologists and active members of the marine conservation NGO), in order to confirm the ecological dynamics of the model, and with resource users (owners and employees of dive schools) regarding dynamics of the tourism sector. Discussions during the games and feedback after 'playing' with KohTaoSim ensured the face validity of actors' behaviour included in the model (Bert et al. 2011, Cooley and Solano 2011). Furthermore, the resulting 'user community view' provides a foundation for evaluation guided by the expectations, anticipations and experience of potential users of the results (Glaser 2012). The main focus was on ensuring the model structure and behaviour captured the main aspects and processes of the actual system of interest (Jopp et al. 2011). This ground truthing approach to model validation corresponds with the idea that 'validity' is dependent on the purpose of the model and consistency with relevant stakeholders' opinions (Ligtenberg et al. 2010, Glaser 2012). Revision by means of ground truthing was an essential part of the iterative modelling process and continued until the model behaviour and results were acceptable to local stakeholders.

2.7 Scenarios

In the previous sections of Chapter II, the iterative and participative modelling processes were explained in detail, including: (1) how social economic data were obtained from the results of empirical studies on Koh Tao; (2) how the results of social studies and ecological data bases were transformed and integrated into the ABM KohTaoSim as model structure, rules, algorithms and parameter values; (3) How KohTaoSim was further tested, revised and validated using traditional statistical methods and non-statistical methods based on ground truthing.

Through these steps, KohTaoSim was set up and confirmed as "ready" by author, local stakeholders and other resource users as adequately reflecting the reality of the dive tourism SES on Koh Tao. In this final section, I show how KohTaoSim was used as a digital laboratory to test a series of "what if" environmental and management scenarios. This allows exploration of environmental dynamics in the SES which may occur infrequently and/or be difficult to study in the real world. It allows alternative management strategies to be tested, without the risk of incurring potentially huge socioeconomic and/or ecological costs associated with decision failure. With this simplified simulation tool, I can yield a holistic and systematic understanding of the coral-based dive tourism SES and apply testing scenarios which it would be impossible to test experimentally in the real world.

The environmental scenarios were developed based on a literature review of current knowledge of ecological factors responsible for declining coral health decline in different regions. The management scenarios were defined based on the original integrated tourism management plan for Koh Tao, which was developed through discussion and voting in monthly meetings of the NGO *Save Koh Tao* and, following appraisal, approved and published by Save Koh Tao and DMCR in 2012 (Hein 2012, Wongthong and Harvey 2014). Different combinations of environmental and management scenarios were tested to simulate the widest possible range of situations that could potentially develop on Koh Tao, including worst-case scenarios. Table 2.13 gives an overview of the scenario conditions and settings that are described in detail in the following section. In each scenario, apart from the test variable(s), all other parameters conform to the standard configuration values described in Section 2.5 'Model parameterization'. The simulation run time was 50 years, allowing time for the processes observed to develop into a dynamic equilibrium. For the purposes of reducing uncertain effects from initialization settings, outcomes of the simulations in the first 10 years will be not shown and included in analysis.

In interpreting the results of the scenarios, it should be borne in mind that KohTaoSim as a simulation tool gives rise to outcomes that are dependent on the data inputs, relations and assumptions built into the model. The aim of KohTaoSim is to offer some scientifically based reflections that contribute to knowledge of complex SES dynamics, and thereby to provide inputs for management decisions, rather than to predict the future.

Table 2.13: An overview of scenario settings and conditions for KohTaoSim.

	Scenario name (short form)	Testing parameter or function	Standard configuration	Scenario condition	Aims, testing effects of
Environmental scenarios	Growth rate (S_E_GR)	Coral health index growth rate (G in Eq. 2)	3.75E-03	–10%, –20%, –30% of standard configuration	Reduction of growth rate due to ocean acidification and ocean temperature change
	Mass mortality (S_E_MM)	Mass mortality event frequency		Every 2, 4 or 8 years	Ocean temperature change, bleaching events, natural disasters, and/or disease
		Mass mortality event strength		10%, 50% or 90% reduction of coral health index (Ht) at shallow sites and, in each case, 60% of the decrease at deep dive sites	
Management scenarios	Indirect damage reduction (S_M_ID)	Indirect damage rate (Di in Eq. 3)	4.2	–10%,-20%, –30%, -40%, –50% of standard configuration	Implementation of waste water plants and/or reforestation
	Artificial dive site (S_M_AD)	Location coordinates of coral restoration sites		Every 5 pixels on the 780*880 pixel simulation environmental grid	Installation of artificial reefs at dive sites (coral restoration)
	Environmental education	Proportion of tourists who	17%	0%, 50% and 100%	Environmental education

	(S_M_EE)	are pro-environmental (pro-environmental rate)			
	Control of visitor numbers (S_M_VN)	Maximum daily tourist number (Tmax) Pro-environmental rate Indirect damage rate (Di)	2400	Low visitor number scenario: -25%; -50%; -75% of standard configuration High visitor number scenario: in 50% increments up to +500% of the standard configuration	Effects of different numbers of visitors as pro-environmental rate changes as indirect damage reduces
Case scenarios	Worst case (S_C_W)	Frequency and strength of mass mortality events, in combination with changes in variables related to scale and impact of tourism		Mass mortality event happens every 2 years and each time reduces coral health index by 90% at shallow dive sites and by 54% at deep sites	In the worst case environmental situation, how does KohTao SES react in following situation: without tourism with tourism with tourism but without an eco-labelling system with tourism and reduction of indirect damage (Di = 2.1) with tourism with eco-labeling with pro-environmental rate = 100%
	Most likely case (S_C_P)	Frequency and strength of mass mortality events, in combination with changes in variables related to scale and impact of tourism		Mass mortality event happens every 7 years and each time reduces coral health index by 50% of at shallow sites and 30% at deep sites	In the most likely environmental situation, how does KohTao SES react in following situation: without tourism with tourism with tourism but without an eco-labelling system with tourism and reduction of indirect damage (Di = 2.1) with tourism with eco-labeling with pro-environmental rate = 100%

2.7.1 Environmental scenarios

S_E_GR: Growth rate change scenarios

Ocean acidification or sea surface temperature rises have been observed to reduce coral growth rates by up to almost 30% in the Pacific Ocean (Manzello 2010) and the Red Sea (Cantin et al. 2010). To explore the consequences of this trend, a range of reductions in coral health index growth rate (–10%, –20% and –30% relative to the standard configuration growth rate) were introduced into simulation to analyse the consequences for the dive tourism SES.

S_E_MM: Mass mortality event scenarios

Various factors may cause mass mortality of corals over a short period of time (Glynn 1993, Wagner et al. 2010). The tsunami in 2004 removed on average 12.5% of live coral cover along the southeast coast of India (Kumaraguru et al. 2005) and nearly 40% in Thailand (Chavanich et al. 2005). Coral disease killed 60% of coral cover in the U.S. Virgin Islands in a bleaching event in 2005 (Miller et al. 2009). A more serious bleaching event, as a result of a prolonged rise in sea surface temperature, led to a 79–92% loss of coral cover in Western Australia in 2010–11 (Depczynski et al. 2013). A dramatic reduction (88%) of live coral cover was also documented along the coast of Tanzania during the 1997–98 bleaching event. On Koh Tao, dramatic declines in coral health were documented in 1988, 1998, 2002 and 2010. In 2014, coral bleaching was observed at all shallow dive sites; however the scale of damage was small and the deep dive sites were not affected on this occasion (information from key informant interviews). Studies indicate that the frequency of mass coral mortality events can be expected to increase due to global climate change (Donner et al. 2005, Riegl and Purkis 2009). The focus of my study is on understanding the impact of such coral mortality events on the dive tourism SES rather than quantifying the amount of damage precisely. Thus I introduce simplified coral mass mortality events into the model with different levels of severity, i.e. high, medium, and low, modelled, respectively, as declines of 90%, 50% and 10% in the coral health index at shallow (snorkel or open water) dive sites and a reduction of up to 60% these magnitudes at deeper (open water and advanced or advanced) dive sites. In different model runs, these events were set to occur at high (every 2 years), medium (every 4years) or low (every 8 years) frequency.

2.7.2 Management scenarios

As reviewed in Chapter I ‘Introduction’, a wide range of management instruments have been developed for sustainable tourism management. Some studies offer management solutions for coral based dive tourism (Rouphael and Hanafy 2007, Wongthong and Harvey 2014), mainly from a social science perspective. The quantitative evaluation of the effects of different management strategies based on the results of scientific research can provide valuable inputs to decision making. KaoTaoSim enables different management options for sustainable tourism development on Koh Tao to be tested in a simulation world before real-life implementation.

Ecological instruments

S_M_ID: On-land pollution reduction scenarios

As reviewed above, and evidenced in the sensitivity analysis, indirect damage is an influential factor affecting coral health. A number of measures have been proposed by *Save Koh Tao* and DMCR to reduce indirect damage. These include the construction of waste water plants and/or small-scale eco-toilet and shower facilities, and a reforestation program. In this scenario it is assumed that these measures are implemented and have the desired effect, leading to a reduction of the indirect damage factor by 10%, 20%, 30%, 40% or 50 %.

S_M_AD: Artificial dive site scenario

Studies worldwide provide evidence of how the construction of artificial reefs can contribute to a reduction of dive pressure on natural reefs and, consequently, to improve health of natural reefs (Leeworthy et al. 2006, Polak and Shashar 2012). In the Gulf of Thailand, there has been growing interest in this idea since the start of the century. Artificial reefs have been the object of the research by local coral ecologists, and increasingly figure in management proposals by NGOs and government agencies. On Koh Tao, an artificial reef zoning plan has been approved by local stakeholders (Hein 2012) and experiments have been underway since 2006 to identify the coral restoration technique that is most suited to local conditions (Yeemin et al. 2006; DMCR 2010a). Whichever technique is suggested (e.g. BioRock or coral nurseries), the cost of coral restoration is likely to be high, and thus the location of coral restoration projects needs to be carefully thought through (Spurgeon and Lindahl 2000). However, the relative efficiency of coral restoration at different locations is hard to predict (Rinkevich 2008), as it depends on dynamical processes unfolding in complex social-ecological systems. GIS maps have been widely used for artificial dive site location selection over the last 2 decades (Tseng et al. 2001, Erftemeijer et al. 2004); more recently, a new method, multiple-criteria decision making analysis (MCDM), has a attracted attention as offering the potential to integrate a range of stakeholder perspectives into GIS analysis (Mousavi et al. 2015). To my knowledge, ABMs have not yet been used for artificial dive site location selection.

KohTaoSim's simulation of the dive tourism SES on Koh Tao and, specifically, the dive site location selection function can be used to estimate the probable efficiency of coral restoration projects at different locations around the island. To this end, I created an artificial dive site at each location (at a resolution of 5 × 5 pixels, i.e. at locations 0,5; 0,10; 5,5 ……) within the simulation environment boundary (740 × 880 pixels, see Figs 1.2 & 2.2). I then documented the simulation results (overall income of all dive schools; average coral health of all natural dive sites; accumulated numbers of tourists and SCUBA divers numbers) over 50 years of simulation time. By ranking and scaling the results from thousands of simulation runs, the efficacy of artificial dive sites at all locations with respect to different management objectives was plotted out as heat maps.

Voluntary instruments

S_M_EE: Environmental education scenarios

Individual attitudes towards the environment influence behaviour and have an impact on conservation outcomes (Pereira 2003, Diedrich 2007). Camp and Fraser (2012) captured significant (56.7%) reduction in physical contact with coral reefs during SCUBA dive after brief conservation education to SCUBA divers. To explore this aspect I tested KohTaoSim with different values of the pro-environmental rate among tourists. This represented a scenario where environmental education successfully changes tourists' attitudes and behaviour, manifested as increased preference for eco-labelled dive schools, donations to the

NGO and diving in a more environmentally friendly way. In model runs, the pro-environmental rate was set at high (100% of tourists), medium (50%) and zero (0%) to compare with standard configuration (17%).

Controlling instruments

S_M_VN: Control of visitor numbers scenarios

As explained in the Introduction, Koh Tao is an isolated island without an airport. I therefore assumed that the transportation capacity, especially the ferry capacity, determines visitor numbers to Koh Tao. Thus controlling visitor number to Koh Tao is possible. I explored the potential ecological and social-economic outcomes of tourist numbers by running the model with different maximum daily tourist numbers, ranging from -75% to of current levels in low visitor number scenario (in 25% decrements) and up to 500% of current level (in 50% increments) in high visitor number scenario. Both high and low visitor number scenarios are tested further in two different sets of scenarios: (a) in combination with environmental educations scenarios (S_M_EE) to explore the extent to which environmental education mitigated the impact of increased numbers of tourists; and (b) in combination with reduced indirect damage scenarios (S_M_ID), to explore the extent to which measures taken to reduce indirect damage mitigated the impact of increased numbers of tourists.

2.7.3 Case scenarios

S_C_P: Most likely scenario

Mass mortality events affected coral reefs on Koh Tao in 1988, 1998, 2002, and 2010 (Table 2.10; Chavanich et al. 2012; Wongthong and Harvey 2014). The documented explanations attribute the mortality mainly to bleaching events (Yeemin et al. 2001, Tun et al. 2004). However, detailed information on the coral health status before and after bleaching is only available for the event that took place in 2010. It was reported that more than 90% of coral colonies experienced bleaching, and the extent of live coral cover was reduced by approximately 50% at shallow dive sites and around 30% at deep dive sites (Chavanich et al. 2012). Thus based on current knowledge, the 'most likely' scenario on Koh Tao was simulated as a situation where a mass mortality event occurs every 7 years causing loss of 50% of coral cover at shallow dive sites and 30% at deeper dive sites. Under this assumption, different model configurations were tested: (1) without tourism activities; (2) with tourism and all variables set at standard configuration values; (3) with continued development of dive tourism on Koh Tao, but where the eco-labelling system has failed; (4) with continued development of dive tourism on Koh Tao, but with better waste water treatment systems and implementation of reforestation programs ($Di = 2.1$). (5) With continued development of dive tourism on Koh Tao, and a very high level environmental awareness among tourists (pro-environmental rate = 100%).

S_C_W: Worst case scenario

In this section, an extremely negative global context for coral conservation was introduced into KohTaoSim to simulate the system's reaction to extreme stress. This 'worst case' includes the occurrence of a mass mortality event every 2 years that removes 90% of healthy coral at shallow dive sites and 50% of coral at deep dive sites. Under this assumption, the same five model configurations were tested as for the most likely scenario.

CHAPTER III SCENARIO EVALUATION

3.1 Environmental aspects

Growth rate change

KohTaoSim was tested with a range of reductions in coral health index growth rate, i.e.–10%, –20% and –30% relative to the configuration growth rate value (3.75E-04). Results showed that the decline in growth rate of coral reef health index threatens reef health status, causing a slight decrease in visitor numbers and profits of dive schools.

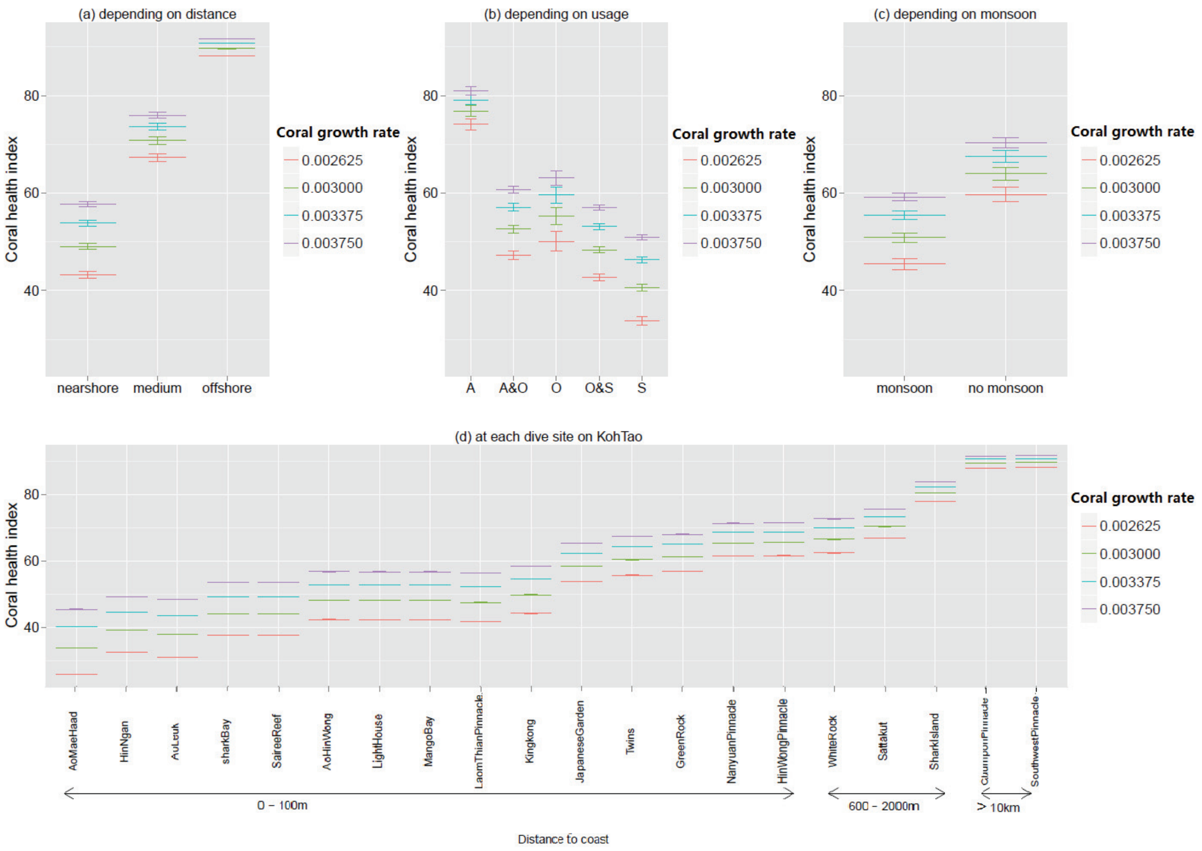


Figure 3.1: Coral health index response to decreasing coral health index growth rate at dive sites grouped according to (a) distance from the coast (nearshore, medium and offshore), (b) dive type (A: advanced SCUBA; O: open water SCUBA; S: snorkeling) and (c) whether or not they are influenced in monsoon season, and (d) at all dive sites ranked according to their distance to coast. The growth rate value in standard configuration was 3.75E-04 (purple line); in tests this value was decreased in 10% decrements to 3.375E-04 (blue), 3.3E-04 (green) and 2.625E-04 (red).

The coral health index of all dive sites decreases when the coral health index growth rate decreases (Fig. 3.1). The decline in coral health index is negatively correlated with the distance from the dive site to the coast (Fig. 3.1a & d). A 10% decline in coral health index growth rate (i.e. to 3.375E-04; light blue lines in Fig. 3.1) leads to declines of 8.3% (SD = 0.91%, n = 45), 3.8 % (SD = 0.9%, n = 9) and 1.18% (SD = 0.08%, n = 6) from standard configuration result at nearshore, middle distance and offshore sites respectively. There was no significant difference of coral health index between dive sites based on the monsoon side and non-monsoon side of the island (1-way ANOVA, $F_{(3,4)}$=0.8127, p=0.5498, Fig. 3.1c), or between different types of dive site (1-way ANOVA, $F_{(3,16)}$=1.0566, p=0.3949, Fig. 3.1b).

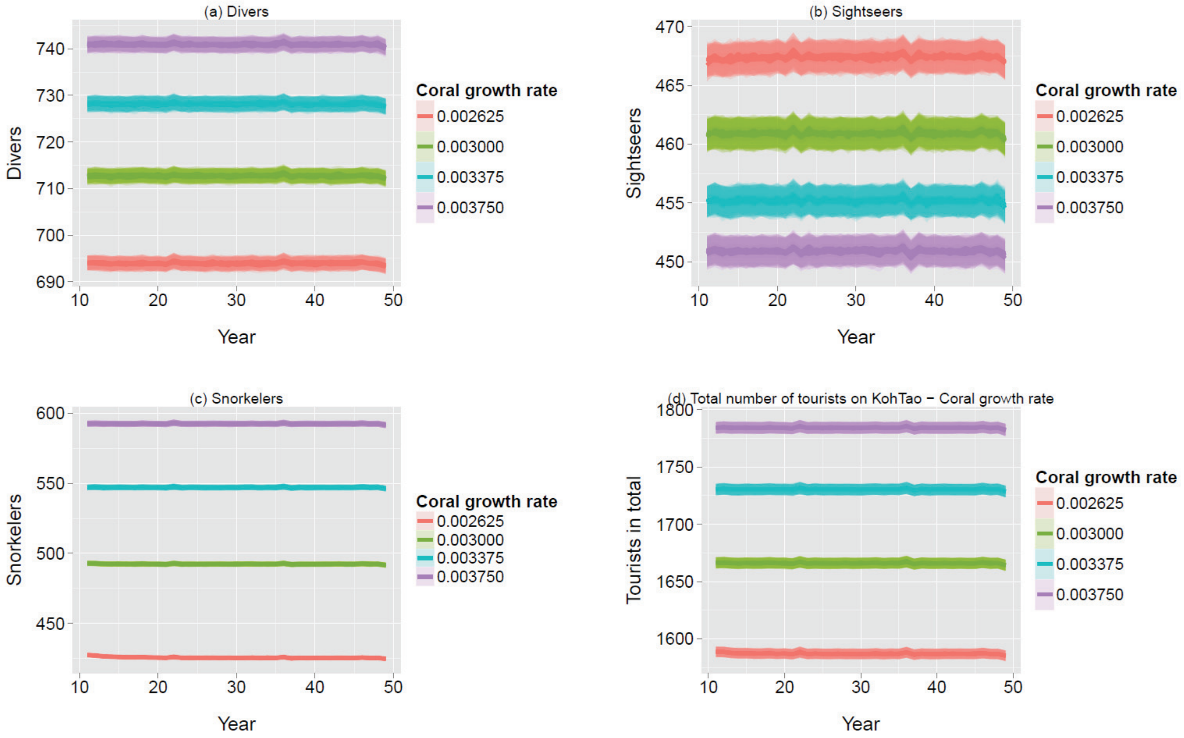
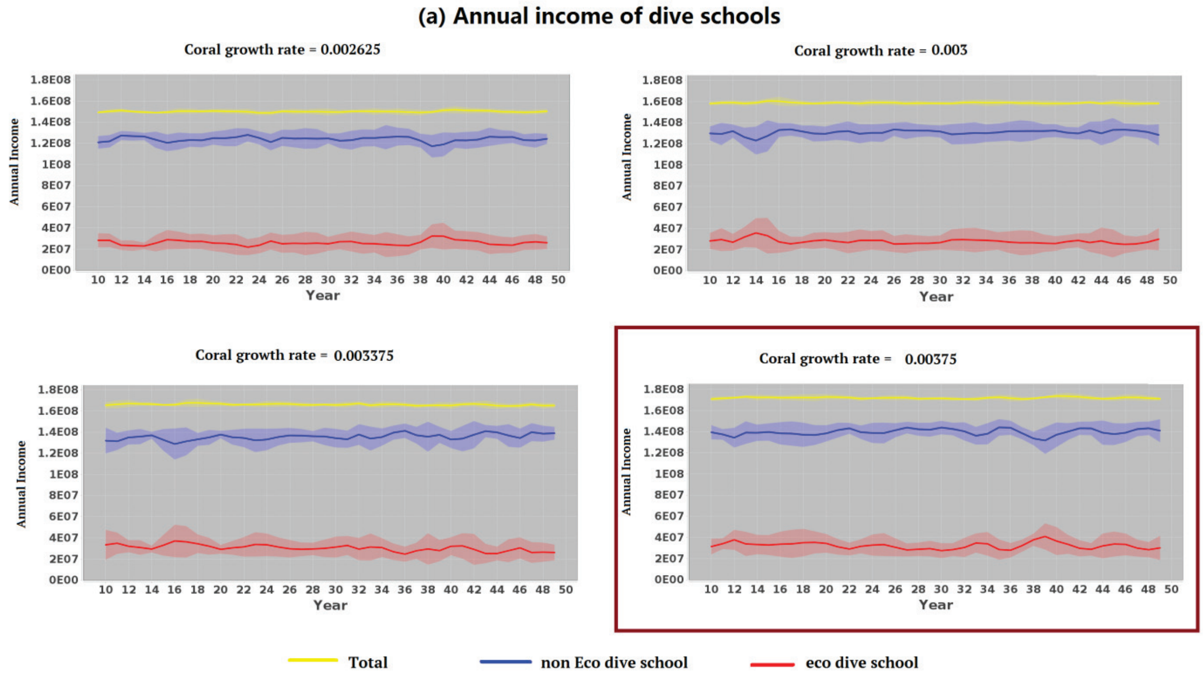


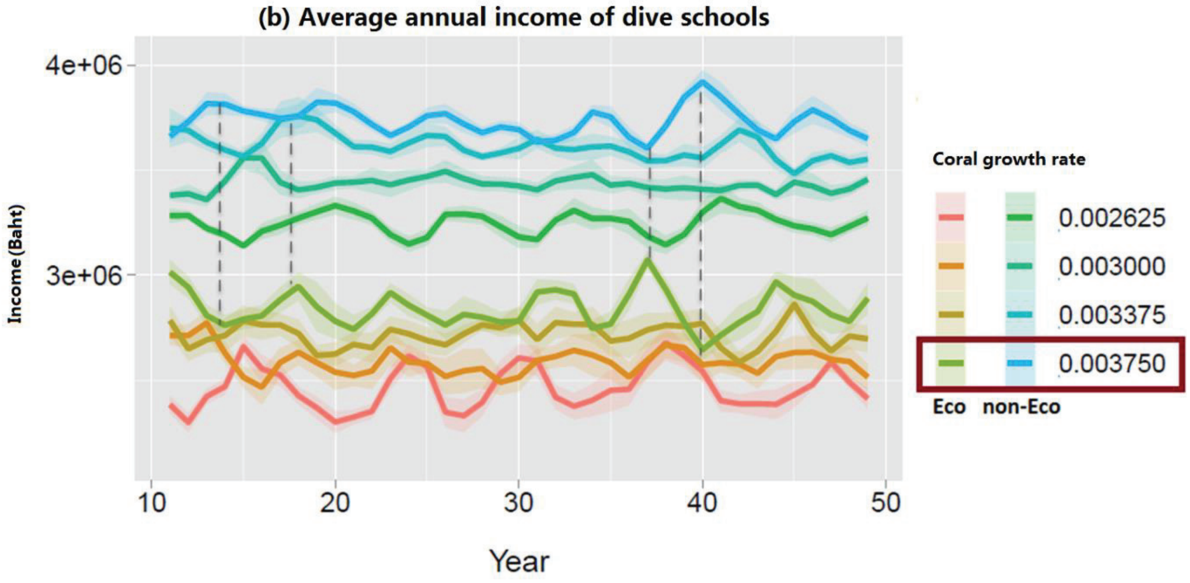
Figure 3.2: Changes in tourist numbers in relation to decreasing coral health index growth rate: (a) SCUBA divers; (b) sightseers (c); snorkelers (d) all tourists. Lines show means and the shaded areas standard errors from 20 simulation runs. The configuration growth rate value was 3.75E-04 (purple line); in tests this value was decreased in 10% decrements to 3.375E-04 (blue), 3.3E-04 (green) and 2.625E-04 (red).

Fig. 3.2 illustrates how the number of tourists decreases as the growth rate of coral health index declines. For all tourists, every 10% decline in coral health index growth rate causes the number of visitors to decline on average by 3.25% from configuration simulation value, i.e 1782 (n = 2118, SD = 95.1) visitors (Fig. 3.2d). Analysis by type of tourist shows that numbers of both SCUBA divers and, to an even greater extent, snorkelers (Fig. 3.2a & c) decline as coral health index growth rates decline, while the number of sightseers (i.e. tourists who do not engage in diving activities) increases. Every 10% decline of coral growth leads to an average of rise 1.3% in the number of sightseers (Fig 3.2 b).

The income of dive schools declines slightly when the rate of coral growth decreases. Taking all dive schools together (community scale), each 10% decline in the coral health index growth rate from the standard configuration leads to a 3.7% decline in mean annual income of over 50 years of simulation, representing economic losses of 6.2E+06 Baht per year (n = 3, SD = 1.1E+06) (Fig. 3.3a).



(a) Annual income of dive schools



(b) Average annual income of dive schools

Figure 3.3: Changes in dive schools' income in relation to decreasing coral health index growth rate (a) Yearly total income of non-eco, eco, and all dive schools for different rates of decline in the coral health index growth rate. (b) Mean annual income of eco- and non-eco dive schools for different rates of decline in the coral health index growth rate over the 50 year simulation. The configuration growth rate value was 3.75E-04 (results shown in red box); in tests this value was decreased in 10% decrements to 3.375E-04, 3.3E-04 and 2.625E-04. Lines show means and the shadow areas indicate standard errors from 20 simulation runs. In panel (b), vertical grey dashed lines link concurrent values for eco and non-eco dive schools.

When individual schools are compared (individual scale, Fig 3.3b), results show slight differences in how they are affected by the reduced coral health index growth rate ($F_{(3,4)}$=0.1037, p=0.9536). The non-eco dive school experiences an average decline in annual income of 4% from each 10% of coral health index growth rate decline from configuration setting, resulting in losses of 1.52+05 Baht per year (n = 3, SD = 4.2E+04). For an eco-dive school, the decline in income is slightly less as 3.8% for 1.18E+05 Baht per year (n = 3, SD = 2.7E+04).

The decline in the rate of growth of coral health index may be caused by different global stressors such as increased ocean acidification and rising sea temperature (Cantin et al. 2010, Manzello 2010), and is likely to have a profound influence on the Koh Tao social-ecological system. In dive sites round Koh Tao, the coral health index declines when the growth rate slows. The findings also indicate that the magnitude of the coral heath index decline is negatively correlated to distance from the coast. Various factors could contribute to this; for example stress from local pollution could be expected to impact nearshore corals more than those located offshore. Some global stress (i.e. sea temperature shift) can also be expected to affect nearshore sites more than offshore ones due to the depth. The total number of visitors, and especially the number of visitors who come to take part in marine activities, decreases due to the decline in coral health. Several studies have shown that satisfaction of marine tourism visitors is largely based on attractiveness of coral reefs (Uyarra et al. 2009, Doiron and Weissenberger 2014). However, other types of visitors are less concerned about the condition of the marine environment. In particular, sightseers base their considerations on whether Koh Tao is (over) crowded or not. Thus, the number of sightseers rises when fewer divers come to the island for other purposes, as shown in Fig 3.2. The model shows that the total income of all dive schools will fall because of decrease in the number of SCUBA divers on Koh Tao. There was no significant difference, however, between eco and non-eco dive schools in terms of income lost as a result of the decline in the number of tourists.

Mass mortality events

Testing scenarios reported in this section include mass mortality events of different strengths and frequencies. A ‘low level’ mass mortality event reduces the of coral health index by 10% at nearshore dive sites and 6% at medium distance or offshore sites. Medium level and high level events reduce the coral health index by 50% and 90%, respectively, at nearshore dive sites and by 30% and 50%, respectively, at offshore sites. In the simulation, the frequency of occurrence of mass mortality events was set at every two, four or eight years.

The overall coral health of dive sites around Koh Tao declines when mass mortality events happen more frequently and when they are more severe (Fig. 3.4). There is a notable difference with respect to reference values when the waters around Koh Tao are affected by high level mortality events. The change in the status of coral health is not as marked for low and medium level events. For example, when the frequency of occurrence is every 8 years, the average coral health of nearshore dive sites in the case of low level events is 57.13 (n = 15, SD = 0.62); for medium level this falls to 51.6 (n = 15, SD = 0.73). But for high level events, the average coral health at nearshore dive sites falls to 30.56 (n = 15, SD= 1.44) after 50 years of simulation (Fig. 3.4a). Meanwhile, simulations without any mass mortality events (standard configuration) result in an average coral health of nearshore dive sites as 52.13 (n = 15, SD = 0.62).

(a) Coral health index at the last year of simulation

(b) Temporal dynamics of coral health index

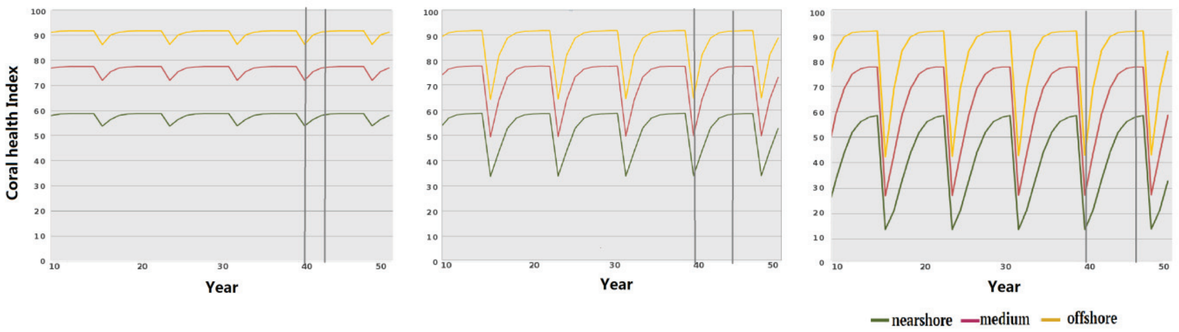


Figure 3.4: Changes in coral health index in relation to different mass mortality event strengths and frequencies: (a) Coral health index of nearshore (green), medium distance (pink) and offshore (yellow) dive sites in the last simulation year under different mass mortality event strengths and frequencies. (b) Coral health index of nearshore, medium distance and offshore dive sites over the course of 50 year simulation with the frequency of events set at 8 years, and sites affected by low (left), medium (centre) and high level (right) events. The distance between the vertical grey lines represents the estimated recovering time for the coral health index.

When the mass mortality level is high and frequent, it has a much stronger effect on nearshore dive sites than on medium distance and offshore dive sites. For example, when the frequency increases from every eight years to every second year, the coral health index at nearshore dive sites decreases from 30.56 (n = 15, SD = 1.44) to 16.61 (n = 15, SD = 2.13), a decrease of 45%. By comparison, the decrease is only 12% in response to the same increase in frequency at medium distance dive sites, while the offshore dive sites are hardly affected by mass mortality events (Fig. 3.4a). Under current model assumptions and algorithms, with regards to the long-term effects of mass mortality events, their influence on coral health is temporary rather than permanent as long as the mass mortality event frequency is longer than coral health index recovery time. The coral health index recovery time is estimated at approximately 2, 4.5 and 7 years following a low level, medium level and high level mass mortality event, respectively (Fig. 3.4b).

The influence of mass mortality events on tourists shows interesting patterns (Fig. 3.5). In general, the number of tourists decreases in line with the strength and frequency of mass mortality events. When the damage level of the event is low, increasing the frequency of events leads to nearly no changes in total visitor numbers or the proportional presence of different types of tourists. When the damage level is high, there is an appreciable change in both total numbers and types of tourist when mass mortality events occur more frequently. More precisely, the total number of visitors is 100,000 in the last year of simulation if events occur every 8 years, of which 27% are SCUBA divers, 31% snorkelers and 42% sightseers. The number drops to 68,000 when events occur every 2 years. At the same time, there is a dramatic change in the proportions of different types of tourist: snorkelers have nearly disappeared, while 53% of tourists are sightseers and 47% are SCUBA divers.

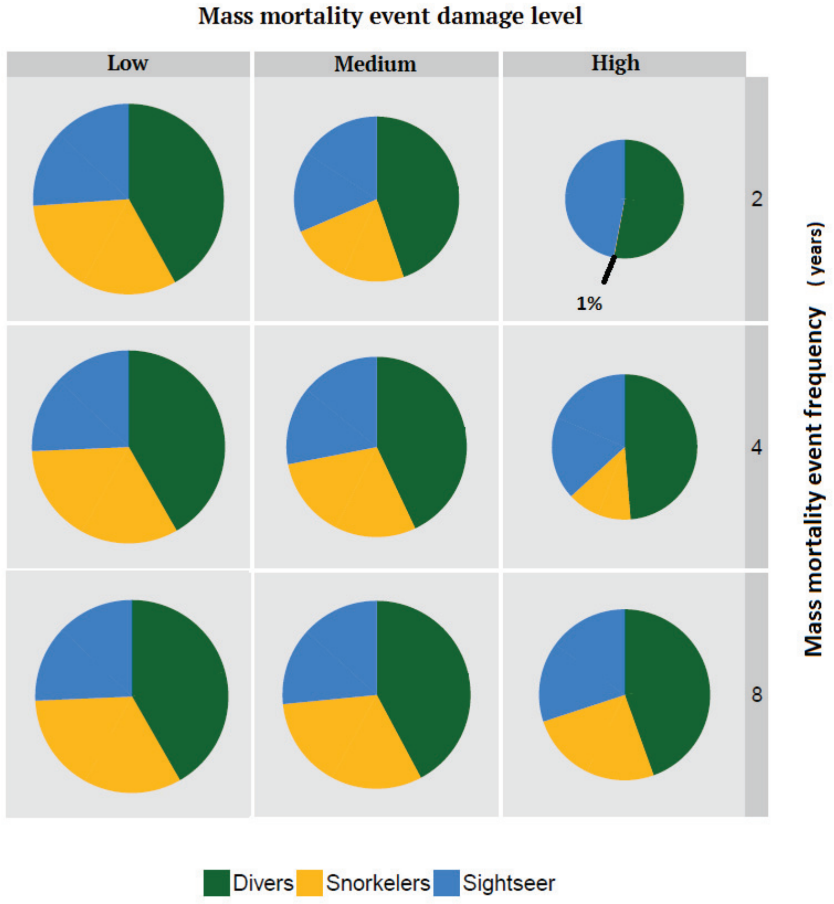


Figure 3.5: Changes in tourist number in relation to different mass mortality event strengths and frequencies: Total visitor numbers (size of pie) and percentage of different types of tourists on Koh Tao in the last year of simulation for different combinations of strength (low, medium or high) and frequency (every 2, 4 or 8 years) of occurrence of mass mortality events. See text for further explanation.

Effects of mass mortality events on income were similar to the impacts on tourist numbers. As the strength and/or frequency of events increases, incomes decline (Fig 3.6). When high level mass mortality events occur every 2 years, they cause huge economic losses. For example, the total income of all dive schools in the final year of simulation drops from 194 million Baht when low level events occur every 8 years to 110 million Baht when high level events occur every 2 years. The NGO influence index also drops from 0.12 to 0.09 under the latter scenario (Fig. 3.6). When the damage caused by the mass mortality event is low, there is no obvious change either in total income of all dive schools or the NGO influence index. However, in all cases, the ratio between total incomes of eco and non- eco dive schools remains stable, with eco and non-eco dive schools accounting for approximately 23% and 77% of total dive school income, respectively.

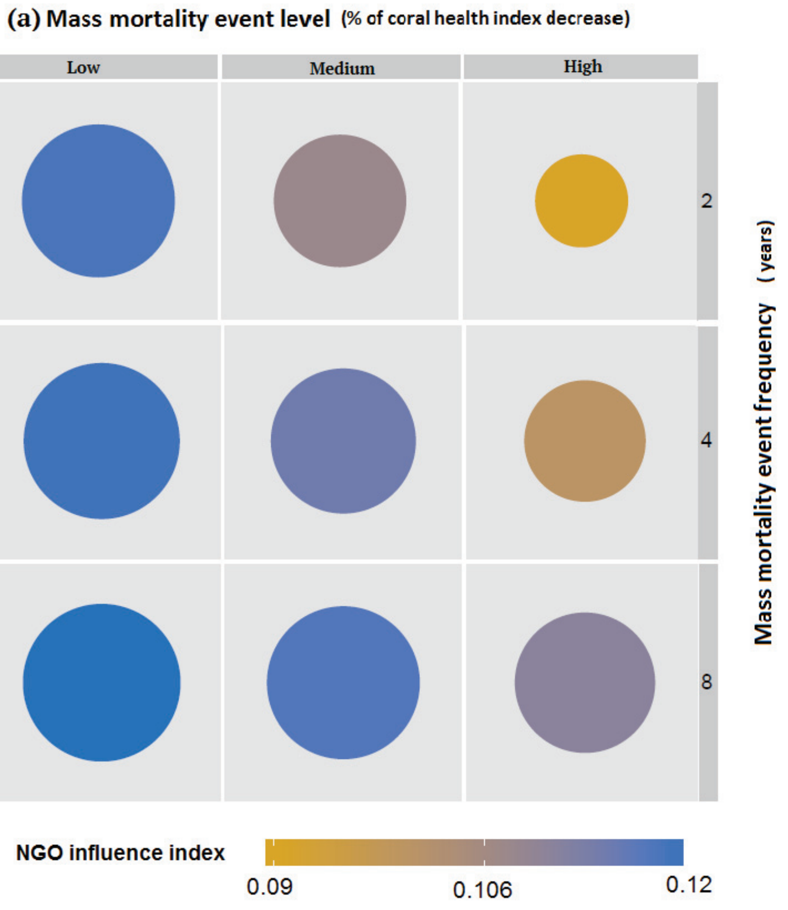


Figure 3.6: Changes in dive schools' income and NGO influence index in relation to different mass mortality event strengths and frequencies: Total income of all the dive schools on Koh Tao (size of the pie) and NGO influence index (color of the pie) in the last year of simulation for different combinations of strength (low, medium or high) and frequency (every 2, 4 or 8 years) of mass mortality events. See text for further explanation.

The model simulation results show that mass mortality events have a very strong influence on the Koh Tao SES. As the damage level and frequency of the events increases, the coral health index declines. This supports similar results in other parts of the globe as reported by several studies (e.g. Ahmed, 2013; Grottoli et al. 2014). The decline in coral health index will eventually cause a reduction in the number of tourists along with the incomes of dive schools. The NGO influence index also decreases. Some authors argue that despite declines the utility of coral dive sites due to mass mortality events, tourists continue to visit the sites (Andersson 2007) and that few economic losses can be detected after mass mortality events in short term

(Westmacott et al. 2000). However, these studies focus on the situation shortly after a mass mortality event, and do not investigate long-term impacts.
Furthermore, according to scenario testing results, when the coral at dive sites around Koh Tao is highly degraded, the type of tourism changes: there is a shift from recreational coral-based dive tourism towards SCUBA dive certification courses (if the cost of getting a dive certificate at Koh Tao remains low) and general sightseeing (because Koh Tao continues to offer hotels and other tourist attractions, such as mountains and beaches). When the intensity of mortality events is medium or low, or when the events are stronger but occur less frequently, the damage to coral damage can be temporary (Fig. 3.4b) and the proportional presence of different types of tourist on the island remains relatively stable (Fig. 3.5).

3.2 Management aspects

Implementation of Coastal pollution control

This section considers the effects of coastal pollution control (i.e. waste water treatment or/and reforestation), leading to a reduction of the indirect damage factor compared to the configuration setting by from –10% to –50% in 10% increments.

The coral health index increases obviously when indirect damage from waste water or sedimentation decreases (Fig. 3.7). This is particularly true for the nearshore dive sites. On average, every 10% reduction in the value of the indirect damage factor increases the coral health index by 6.7% (n = 15, SD = 1.1%) when simulated with standard parameter settings (coral health index mean = 58.1, SD = 5.13, n = 15). For dive sites located at a medium distance from the coast, the coral health index increases on average by 2.8% when the indirect damage factor decreases by 10% from the standard configuration (n = 3, mean = 76.25 SD = 4.79). For offshore dive sites, the influence is small (Fig 3.7a). Interestingly, there is no significant difference between effects on dive sites on the monsoon-influenced side of island and sites on the other side that are not influenced by the monsoon (1-way ANOVA, $F_{(5,6)}$=1.242, p=0.3940, Fig 3.7c), or among different types of dive site (1-way ANOVA, $F_{(5,24)}$=1.4482, p=0.2434, Fig 3.7b).

Simulation results showed that the total number of tourists increases when the indirect damage factor declines. On average, each 10% decline in the value of the indirect damage factor leads to a 2.3% (n = 4, SD = 0.00125) increase in visitor numbers. When indirect damage decreases by 50%, Koh Tao hosts on average 1993 (n = 20, SD = 107) tourists per day, compared with 1784 (n = 20, SD = 95.04) under the standard configuration. Changes observed due reduced indirect damage on numbers of different types of tourists are summarized in Fig. 3.8. Numbers of both SCUBA divers and, especially, snorkelers increase when indirect damage is reduced. However, the number of sightseers decreases slightly.

The effects of reducing the indirect damage rate on income are shown in Fig. 3.9. In general, dive schools' incomes rise as the value of the indirect damage factor falls. When considered at community scale (Fig. 3.9a), for each 10% decline in the indirect damage factor, the mean annual income of all dive schools over 50 years of simulation increases by 2.1% from configuration setting (4.2E+06 Baht, SD= 4.4E+05, n = 6). At the individual scale (Fig. 3.9b), for both non-eco and eco-dive schools, a 10% decline in indirect damage leads to a 2% mean increase in annual income (2% of eco-dive school annual income: mean = 7.4E+04 Baht, SD = 2.2E+04, n = 6; 2% of non-eco dive school annual income: mean = 9.2E+04 Baht, SD = 2.7E+04, n = 6). .

In summary, a decrease in the indirect damage to the marine environment caused by human activities on Koh Tao leads to an obvious improvement in coral reef health, as evidenced not only in this study but also worldwide (Wear and Thurber 2015). Such positive effects can occur as a result of reduced inputs of dissolved nutrients, sedimentation or particulate organic matter into coral ecosystems (Fabricius 2005) leading not only to more extensive live coral cover but also to increased biodiversity of the coral ecosystem (Edinger et al. 1998). Improved coral health attracts slightly more SCUBA divers and significantly more snorkelers to Koh Tao, thereby increasing the incomes of dive schools. On the other hand, the increased presence of divers means that the island is more crowded and attracts fewer sightseers.

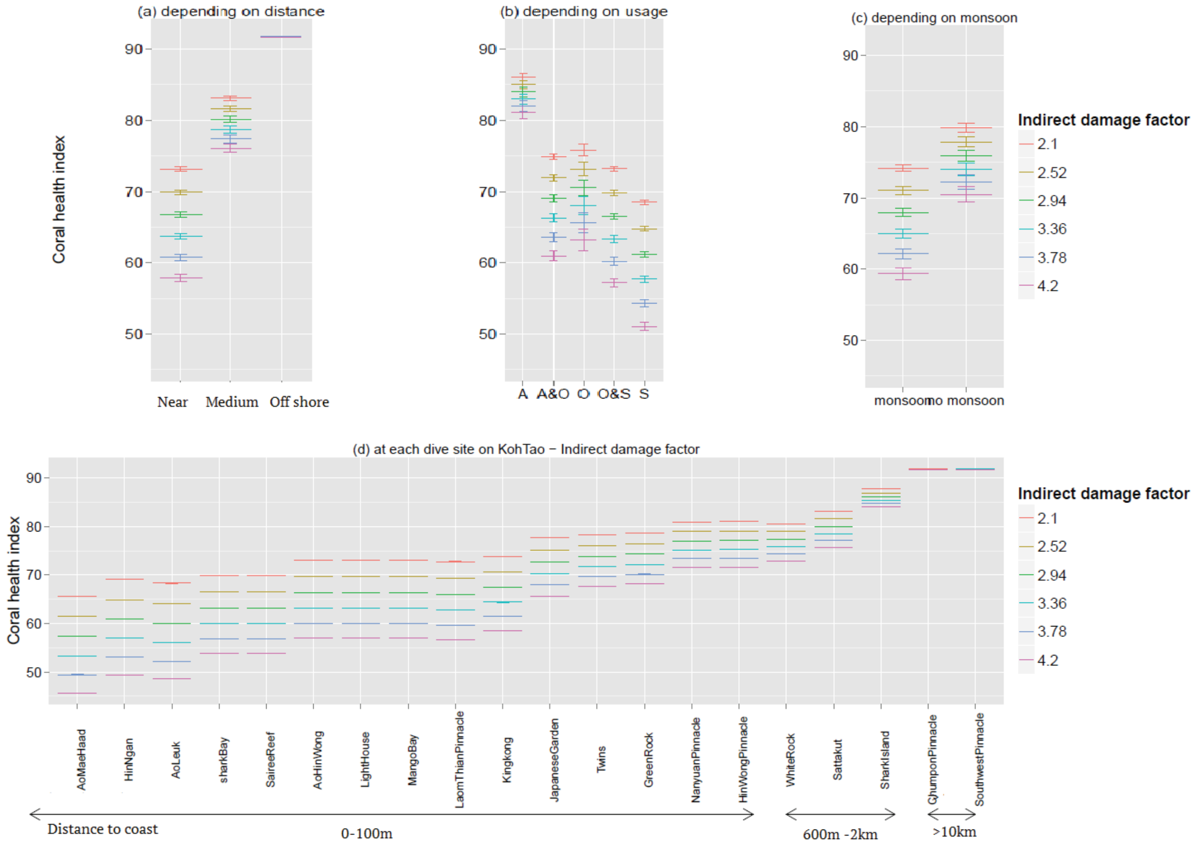


Figure 3.7: Coral health index response to decreased indirect damage: at dive sites grouped according to (a) distance from the coast (nearshore, medium and offshore), (b) dive type (A: advanced SCUBA; O: open water SCUBA; S: snorkeling) and (c) whether or not they are influenced in monsoon season; and (d) at all dive sites ranked according to their distance to coast. The configuration value of the indirect damage factor was 4.2, and this was decreased in five 10% decrements to 2.1 (i.e. half the configuration value).

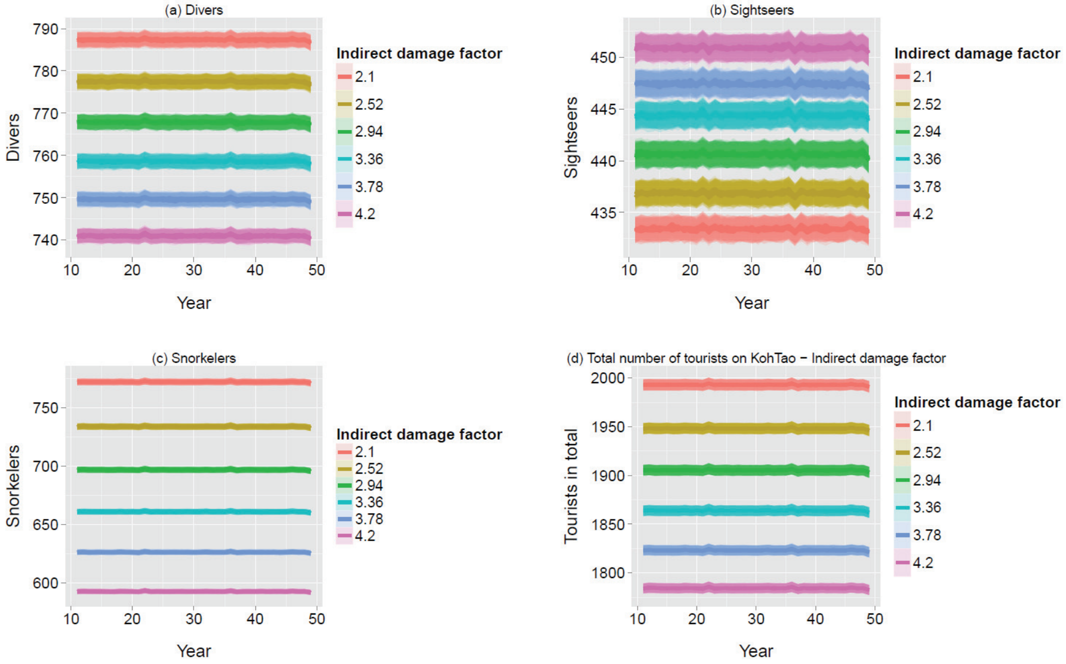
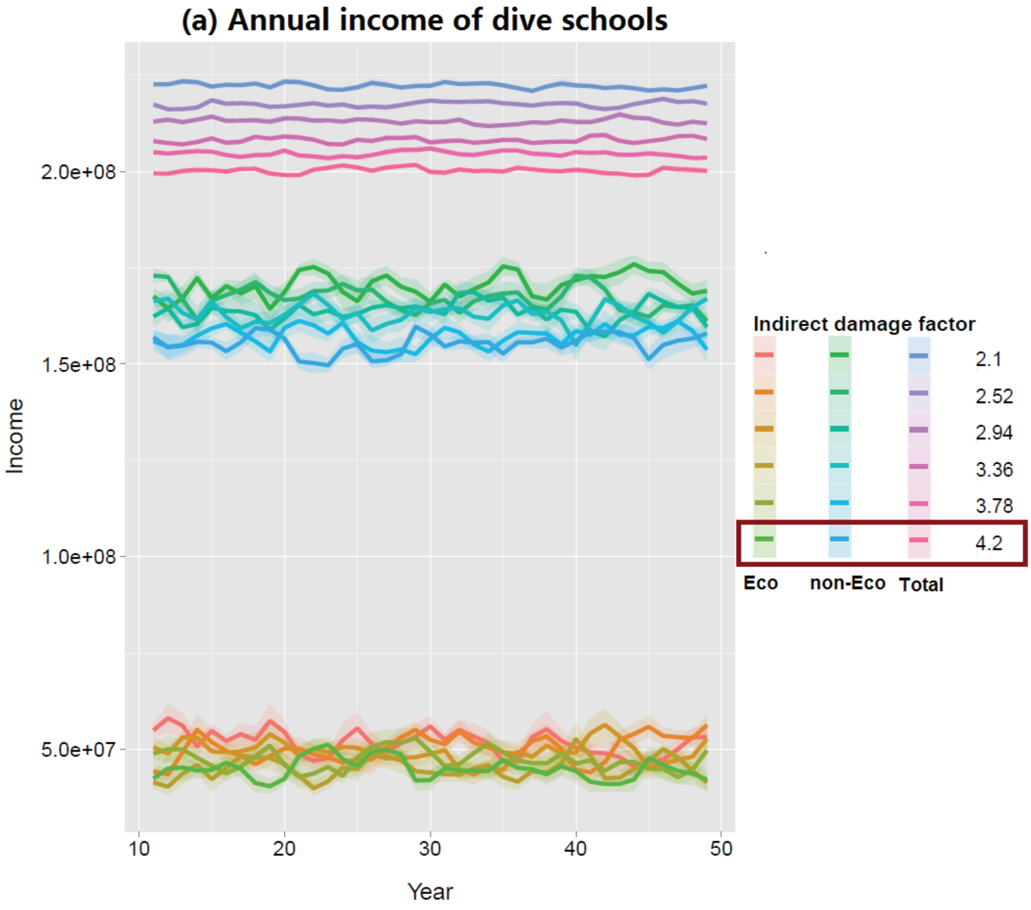


Figure 3.8: Effects of decreased indirect damage on tourist numbers: (a) SCUBA divers; (b) sightseers (c); snorkelers (d) all tourists. Lines show means and the shaded areas indicate standard errors from 20 simulation runs. The configuration value of the indirect damage factor was 4.2, and this was decreased in five 10% decrements to 2.1.



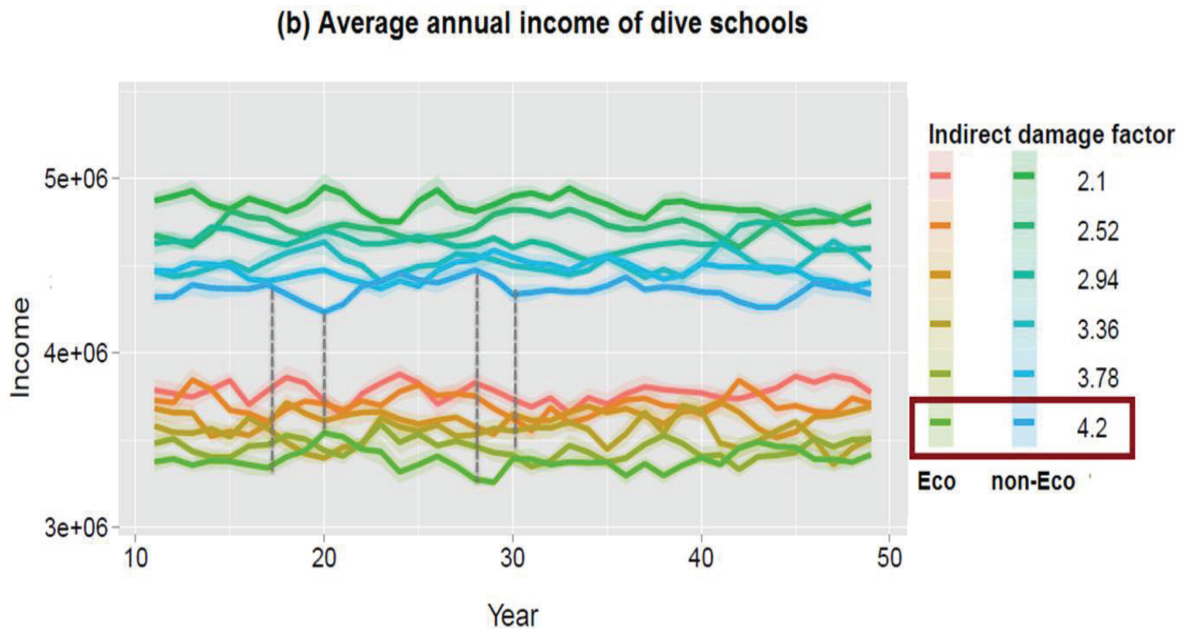


Figure 3.9: Changes in dive schools' income in relation to decreasing indirect damage factor: (a) Total annual income of non-eco, eco, and all dive schools for different rates of reduction in the indirect damage factor. (b) Mean annual income of eco- and non-eco dive schools for different rates of reduction in the indirect damage factor along the 50 year simulation. The standard configuration value of the indirect damage factor was 4.2, and this was decreased in five 10% decrements to 2.1. Lines show means and the shadow areas indicate standard errors from 20 simulation runs. In panel (b), vertical grey dashed lines link concurrent values for eco and non-eco dive schools.

Implementation of artificial dive site

This section investigates the effectiveness of artificial dive sites at different location around Koh Tao in improving the health of natural coral dive sites, increasing the income of the dive-based tourism industry and reducing dive pressure on natural dive sites. Results are shown as heat maps that depict the outcomes of constructing artificial dive sites at all locations around Koh Tao. It should be noted that the maps do not show the results of a single simulation; rather each square in heat map plots the result of a simulation where one extra dive site was added at the corresponding location.

Firstly, overall coral health is not improved by the construction of an artificial dive site. By adding an artificial dive site at the most effective location, the average coral health index of all natural dive sites is 65.1, while when one is added at the least effective location the value of the coral health index is 64.9, which brings no difference from standard configuration result (with no artificial dive site). Thus the location of an artificial dive site is not important if the aim is to improve the coral health of natural dive sites (Fig. 3.10 a). The effectiveness in attracting additional tourists (Fig. 3.10b) or SCUBA divers (Fig. 3.10c) to the island is positively correlated with the distance of the artificial dive site from the coast within the tested area. However, once again, in both cases the range of values between the most and least effective sites are low. Thus the location of an artificial dive site does not greatly affect its effectiveness in attracting more tourists to the island.

Importantly, the model shows that the construction of an artificial dive site is very effective in increasing the total income of all dive schools and, furthermore, the location of the site is very influential (Fig. 3.10d). The west coast including Sairree beach and Aomaehaad towards southwest end of Koh Tao are the best locations, where an artificial dive site generates a maximum of 11 billion Baht of accumulated income for all dive schools, which is 112.2 % of the total income without artificial dive site. However, according to the heat map, the location should not be directly next to the coast line, where the artificial dive site is affected by indirect damage from Koh Tao Island. Most interestingly, constructing an artificial dive site could be a very effective way to decrease the dive pressure at natural dive sites (Fig. 3.10e). This is especially true at the most effective location (between Sairree beach and Aomaehaad) where an artificial site reduces dive pressure on natural sites by up to 31%. Even though this does not improve coral health at adjacent natural sites, it does make the SCUBA dive experience less crowded. In comparison with the income heat map (Fig. 3.10d), the most effective location for an artificial dive site in terms of reducing dive pressure shifts slightly further north, towards Koh Nang Yuan. However, in statistical model validation exercises to evaluate KohTaoSim, it was found that the dive pressure around Koh Nang Yuan is generally over estimated by KohTaoSim compared with the empirical data. It worth to explain that there is a clear division between west and east sides of the island in some of the heat maps (Fig. 3.10a & e). This is due to the algorithm used in KohTaoSim to define the area influenced by the monsoon. The left (west) side of the island is not influenced by monsoon, but the right (east) side is.

As a summary, construction of an artificial dive site leads to an increase in community income and greatly reduces dive pressure at popular dive sites. These findings concur with Hein (2012) who showed that artificial dive sites around Koh Tao can be effective in reducing dive pressure at natural dive sites. The reduction in dive pressure is basically the result of redirecting underwater activities from natural coral reefs to artificial reefs, thereby protecting the reef environment while meeting the demand for scuba-diving. Studies carried out in Florida, USA and Red Sea both demonstrated the positive effects of an artificial dive site on incomes of local businesses and the employment rate (Leeworthy et al. 2006, Polak and Shashar 2012). However, Spurgeon and Lindahl (2000) argue that coral restoration is not a cost-effective solution due to high construction and maintenance costs. Additionally, by contrast, in the present study, an artificial dive site has no obvious direct effect on numbers of SCUBA divers coming to the island or the health of natural coral reefs.

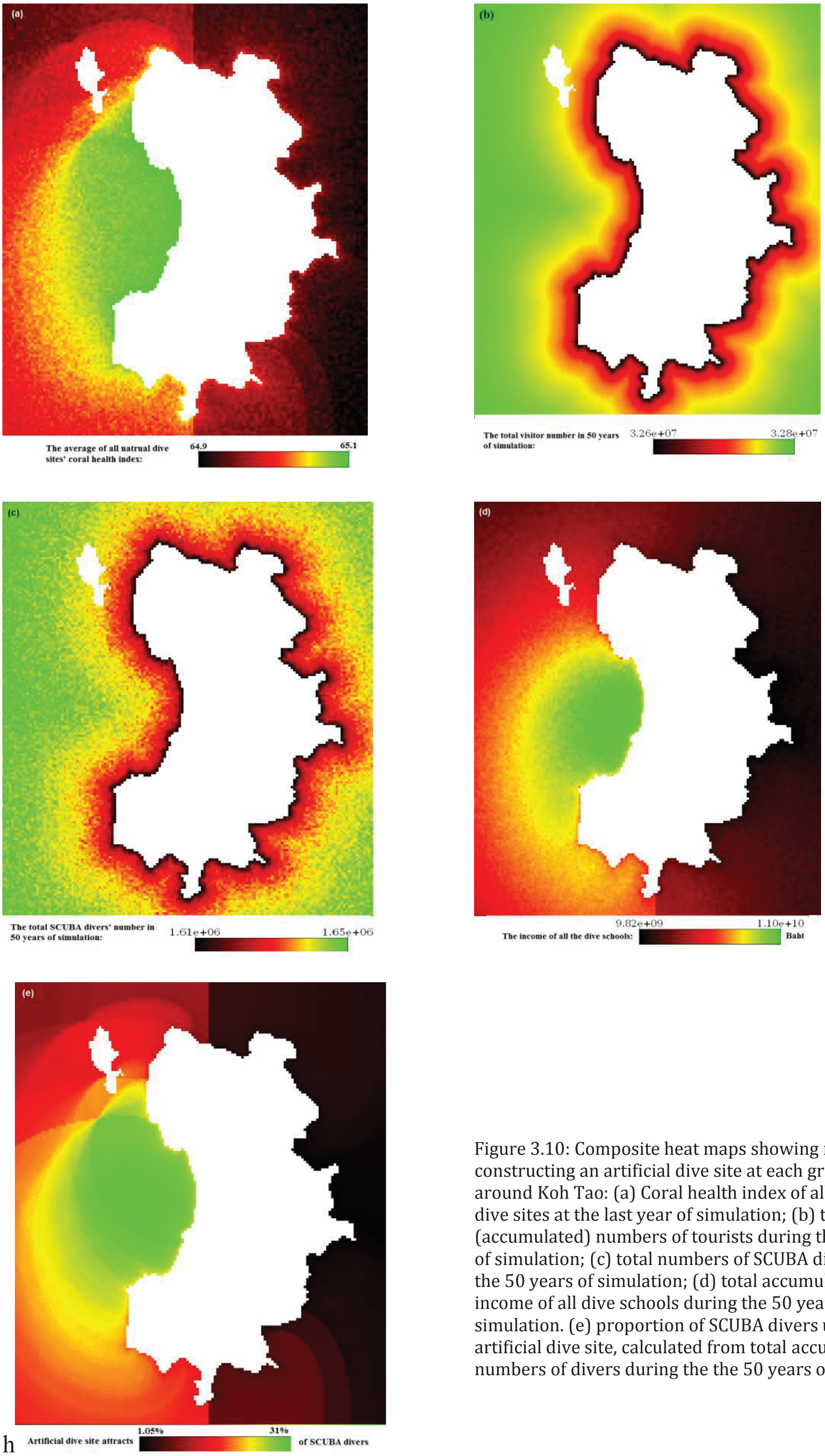


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Figure 3.10: Composite heat maps showing results of constructing an artificial dive site at each grid location around Koh Tao: (a) Coral health index of all natural dive sites at the last year of simulation; (b) total (accumulated) numbers of tourists during the 50 years of simulation; (c) total numbers of SCUBA divers during the 50 years of simulation; (d) total accumulated income of all dive schools during the 50 years of simulation. (e) proportion of SCUBA divers using the artificial dive site, calculated from total accumulated numbers of divers during the the 50 years of simulation

Environmental education programmes

This section reports the results of varying the pro-environmental rate of visitors to Koh Tao, as a result of increasing or decreasing the amount of environmental education provided to tourists. I asked, what would Koh Tao look like if the pro-environmental rate was high (100% of tourists), medium (50%) and zero (0%), in comparison to the standard configuration setting (17%). The findings show no obvious effect on the coral health index, visitor numbers or numbers of different types of tourists. However, with a high pro-environmental rate, the average income of eco-dive schools rises. The development curves (Fig. 3.11), show that with a medium or high pro-environmental rate eco-dive schools make much more money than non-eco dive schools at the start of the simulation, as only 3 dive schools are initialized as eco dive school as a simulation of empirical investigation result. The magnitude and duration of this advantage is positively correlated to pro-environmental rate. However, in all simulation cases the advantage is relatively short lived and by the end of the simulation non-eco dive schools are earning more. The observed dynamic is the result of competitive interaction between eco and non-eco dive schools. This phenomenon also affects results reported in other sections (cf. Figs. 3.3b, 3.9b, 3.22b). Furthermore, when the pro-environmental rate is higher, the standard error (shaded area) is larger. This indicates that the process is becoming more random. The reason for such increase in system randomness can be due to the high random level of eco status involved processes (i.e. the process of how SCUBA divers select dive schools and how tourists decide on their eco status). Overall, as shown in Fig.3.11, the chances of eco-dive schools making as much money as non-eco-dive schools increase with the increase in pro-environmental rate. However, it is important to emphasize that in all scenarios, over the entire simulation period, there is a very high probability that non-eco dive schools will make more money than eco-dive schools.

Fig, 3.12 shows that the NGO influence index and total income of dive schools increase when the pro-environmental rate increases. However, the annual income of all dive schools increases by only 3.5% when the pro-environmental rate shifts from 0% to 100%. Moreover the percentage of total income earned by eco-dive schools increases dramatically when the pro-environmental rate increases. For example, when the pro-environmental rate is 0%, over the 50 years of the simulation, eco-dive schools receive an average of 11.8% (n = 50, SD = 1.57%) of the total annual income of all dive schools. When the pro-environmental rate 100%, eco-dive schools income represents 36.3% (n = 50, SD= 3.32%) of total annual income.

A change in the pro-environmental rate can influence the distribution of SCUBA divers at non-snorkeling sites. When the pro-environmental rate increases from 0% to 100%, the dive pressure decreases at heavily used dive sites (A&O and O) and increases at others. The magnitudes of the changes is up to +21% for advanced dive sites, +51% for open water and snorkeling sites, –1.4% for open water and advanced dive sites and –7% for open water dive sites.

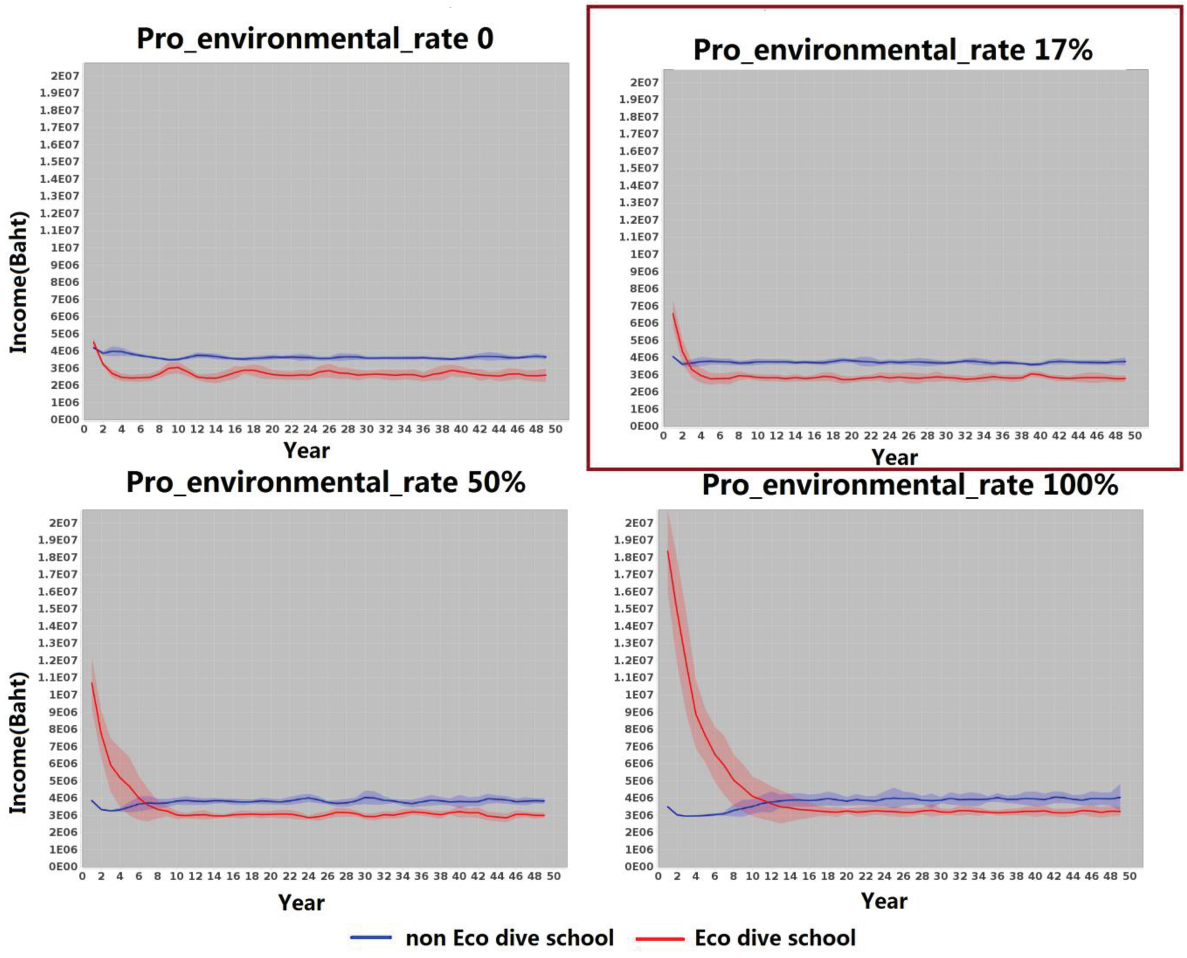


Figure 3.11: Mean annual income of eco- dive schools and non-eco dive schools under different pro-environmental rates over the course of the simulation. Values are in Baht; the shaded areas show the standard errors of all simulation runs. The standard configuration situation is outlined in red.

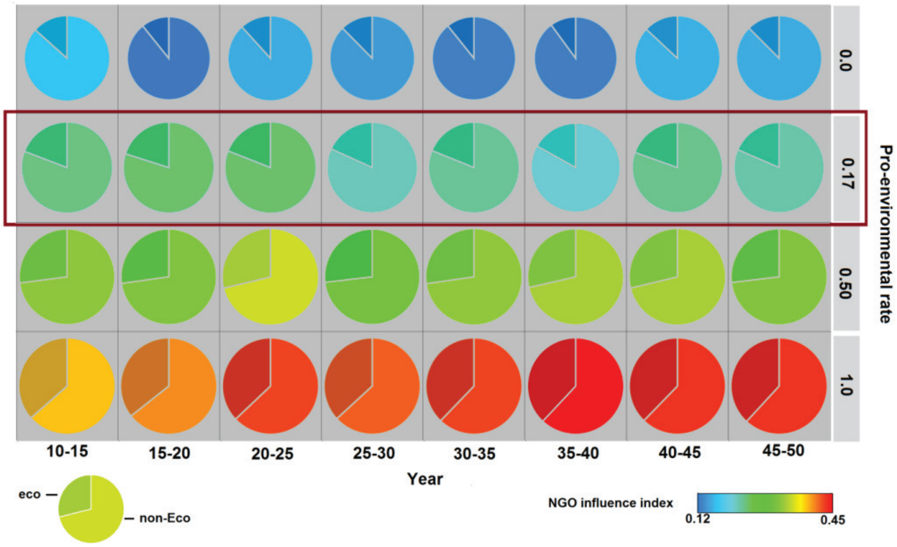


Figure 3.12: Effects of increasing the pro-environmental rate on dive schools' income and NGO influence index: in 5-year time periods over the course of the simulation, showing the average annual income of all dive schools (size of pie), the NGO influence index (colour of pie), and relative proportion of total dive schools income received by eco- and non-eco dives schools (segments of pie). The standard configuration situation is outlined in red.

In summary, programs aimed at public education will not help obviously to improve the coral health index at dive sites around Koh Tao. Indeed, such programs will not influence the number or type of visitors on Koh Tao**.** Similarly, fisheries scientists have not found much direct evidence that eco-labeling has a positive influence on fish stocks (Erskine and Collins 1997, Jacquet et al. 2009, Stokstad 2011). However, the overall income of all dive schools is slightly increased by increasing environmental awareness among tourists, as more SCUBA divers will be willing to pay for an eco-labeled dive school. This increase, however, is not significant across the whole community. In the short term a higher pro-environmental rates leads to significantly higher incomes for eco-dive schools. However, due to market competition, eco-dive schools quickly lose this competitive advantage and are highly unlikely to make more money than non-eco dive schools in a long term. This could be due to the fact that when the eco-dive schools make more money than non-eco schools, then more dive schools transform themselves into eco-dive schools, thereby reducing the average profit of eco-dive schools. When there are so many eco-dive schools that eco-labeling confers little benefit, then more schools are likely to opt to forego the additional costs associated with eco-labeling, and convert (back) to non-eco dive schools. However, in simulations, this dynamic balance usually ends up with non-eco-dive schools making, on average, more money than eco-dive schools. Interestingly, public education together with eco-labeling system (which determines how dive schools select dive sites) can be effective in reducing the dive pressure at heavily dived sites around Koh Tao. This is because, the environmental awareness leads dive schools to opt for less crowded dive sites, rather ones with the highest coral health. This model configuration reflects the empirical results of field work carried out in the initial phase of the study. The decrease in dive pressure at popular sites is likely to increase the quality of SCUBA divers' dive experience.

Implementation of visitor number control

In order to explore the impact of tourist numbers on the coral-based dive tourism SES, KohTaoSim was tested under a range of tourism scenarios, with maximum tourist numbers (estimated as daily transportation capacity multiply with average stay duration of tourists, hereafter 'tourist maximum') set at values both lower (from 600 to 2400) and higher (from 2400 to 12,000) than the configuration setting. Results showed that tourist numbers have a considerable influence on the coral health index (Fig. A5.1 in App. 5). For example, when the tourist maximum is low the mean coral health index at all sites increases. Specifically a 50% decline in the tourist maximum (from 2400 to 1200) leads to a 15.4% increase in the average coral health index at all dive sites. When the tourist maximum falls to 600 (less than the threshold value of tourist number for no indirect influence on coral reefs), the value of the coral health index rises to 41.2% above the configuration value, staying in a very healthy condition (mean=91.7, SD=0.82, n=20). By contrast a 50% increase in the tourist maximum from 2400 to 3600 leads to an average decrease of 11% in the coral health index. The decline is less marked at dive sites further away from the coast and most dramatic at snorkeling sites. When the tourist maximum exceeds 8400, the coral health index drops to 0 at snorkeling sites (Fig. A5.1).

When the tourist maximum increases, tourist numbers also increase. However, when daily visitor numbers exceed 1000, the number of visitors does not reach the tourist maximum (Fig 3.13 and Fig. A5.2). This is particularly true in scenarios with high maximum tourist number (Fig. 3.13). For example, when the tourist maximum is defined as 12000, simulated daily visitor numbers are only approximately 6000 (half of the tourist maximum). In general, proportions of SCUBA diver and sightseers stay relatively stable, especially in scenarios with low visitor numbers (Fig. A5.2). Under scenarios with high visitor numbers, a very slight decline in the number of SCUBA divers and a weak increase in the number of sightseers can be observed (Fig. 3.13 a & b). The number of snorkelers never exceeds 800 per day in KohTaoSim. When the tourist max is less than 4800, the number of snorkelers is positively correlated to the tourist maximum. When the tourist maximum is set between 4800 and 7200, the number of snorkelers remains at 800 throughout the simulation period. However, when the tourist maximum number is more than 7200, the number of snorkelers at the end of the simulation is inversely related to the tourist maximum (Fig. 3.13c). As the tourist maximum rises, the number of visitors arriving on the island each day also rises but at a slower rate. For example, when the tourist maximum is 2400 and the daily transportation capacity (i.e. the number of tourists who can arrive on Koh Tao on any one day, defined as 20% of the tourist maximum) is 480, the average number of arrivals on the island is estimated by KohTaoSim as 305 per day (SD = 61, n = 50). On average, the occupation rate of transportation to Koh Tao (numbers of arrivals as a percentage of transportation capacity) will be 63.5%. By contrast when the tourist maximum is 12,000, the transportation is 2400 but there are only 1006 estimated new arrivals per day; therefore the occupation rate of transportation falls to 41.9%.

The total income of all dive schools is positively correlated to the tourist maximum; as is to be expected since more tourists generate higher incomes (Fig. A5.3). For example when the tourist maximum decreases from 2400 to 1200, the estimated average annual income in the final 5 years of the simulation falls from 200 million Baht (n = 55, SD = 2.9E+06) to 38.1 million Baht (n = 55, SD = 1.0E+06). The decline is equivalent to 80.9%. In contrast, an increase in the tourist maximum from 2400 to 3600 brings a 62.3% increase in average annual income in the final five years of the simulation. No upper limit to the overall income of dive schools was observed in the testing scenarios. Moreover, increasing numbers of tourists leads to an increase in the NGO influence index and, indirectly, in the incomes of the eco-dive schools.

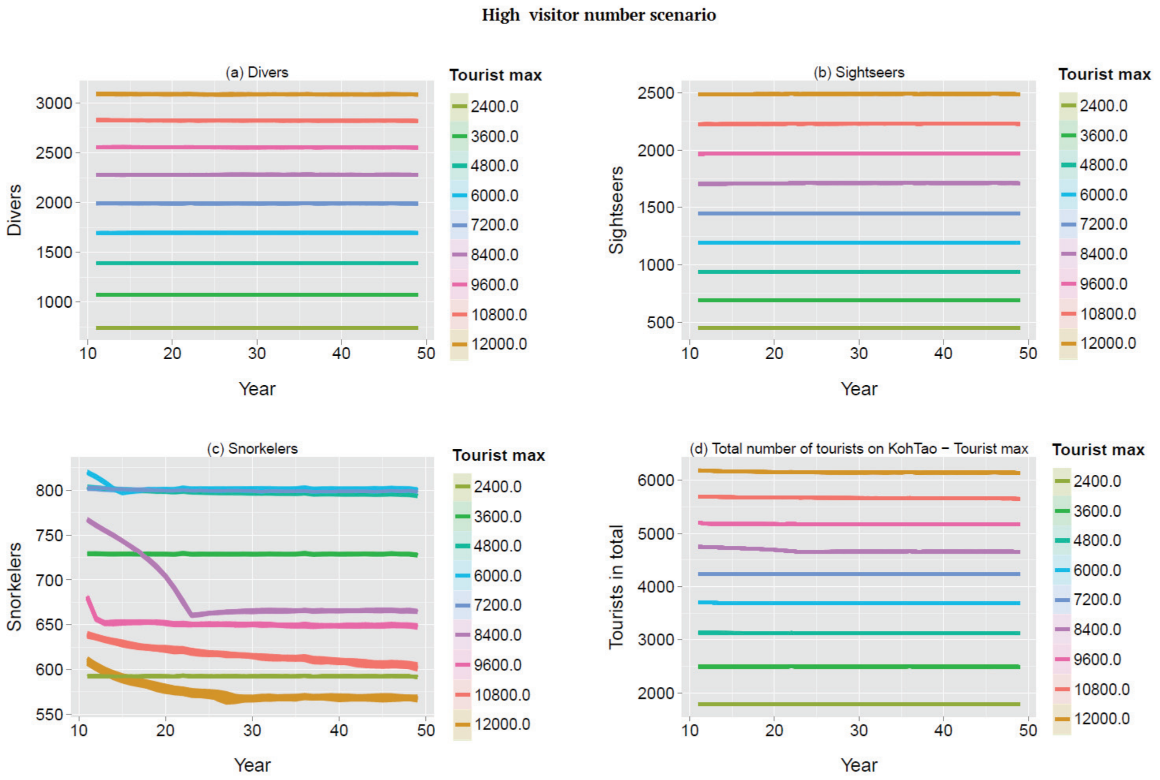


Figure 3.13: Simulated daily tourist numbers on Koh Tao for different values of the tourist maximum in high visitor number scenarios (from the configuration value of 2400 to 12,000): (a) SCUBA divers (b) sightseers (c) snorkelers (d) all tourists. The lines show means and the shaded areas indicate standard errors.

Implementation of visitor number control and other management tools

This section reports the results from tests on the effects of different value combinations of the tourist maximum, the pro environmental rate and the indirect damage factor. The aim was to investigate the potential of a combination of controls on tourist numbers together with other management strategies (i.e. public education, and waste water treatment and reforestation) to contribute to the sustainability of tourism development on Koh Tao.

When changes in visitor numbers are combined with measures to improve environmental education, the results indicate that public education is unable to offset the negative effect on coral health of increasing visitor numbers and has little positive effect if tourist numbers remain the same (Fig. 3.14). For example, when the tourist maximum is maintained as the standard configuration of 2400 and the pro-environmental rate is increased from 17% to 100% the coral health index is increases by only 0.4% at nearshore dive sites (57.89 to 58.1) and by a similar proportion at sites further from the shore (Fig. 3.14). When the tourist maximum is maintained at 2400 and the number of annual visitors remains 110,000, while the pro-environmental rate is increased from 17% to 100%, the total income of all dive schools in the final year of the simulation increases by 4.1% from 200 million Baht to 208 million Baht.

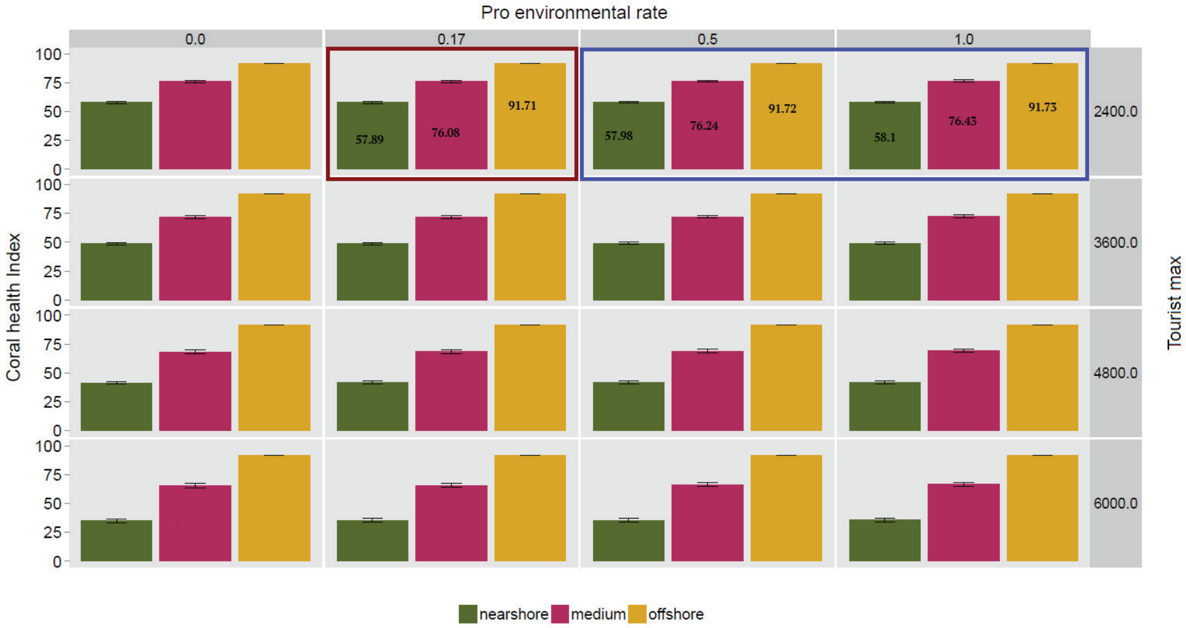


Figure 3.14: Coral health index response to different combinations of the tourist maximum and the pro-environmental rate: Average coral health index of nearshore (green), medium distance (pink) and offshore (yellow) dive sites in the final simulation year under. The standard configuration is outlined in red; the area outlined in blue encloses cases where the coral health index is higher than the standard configuration.

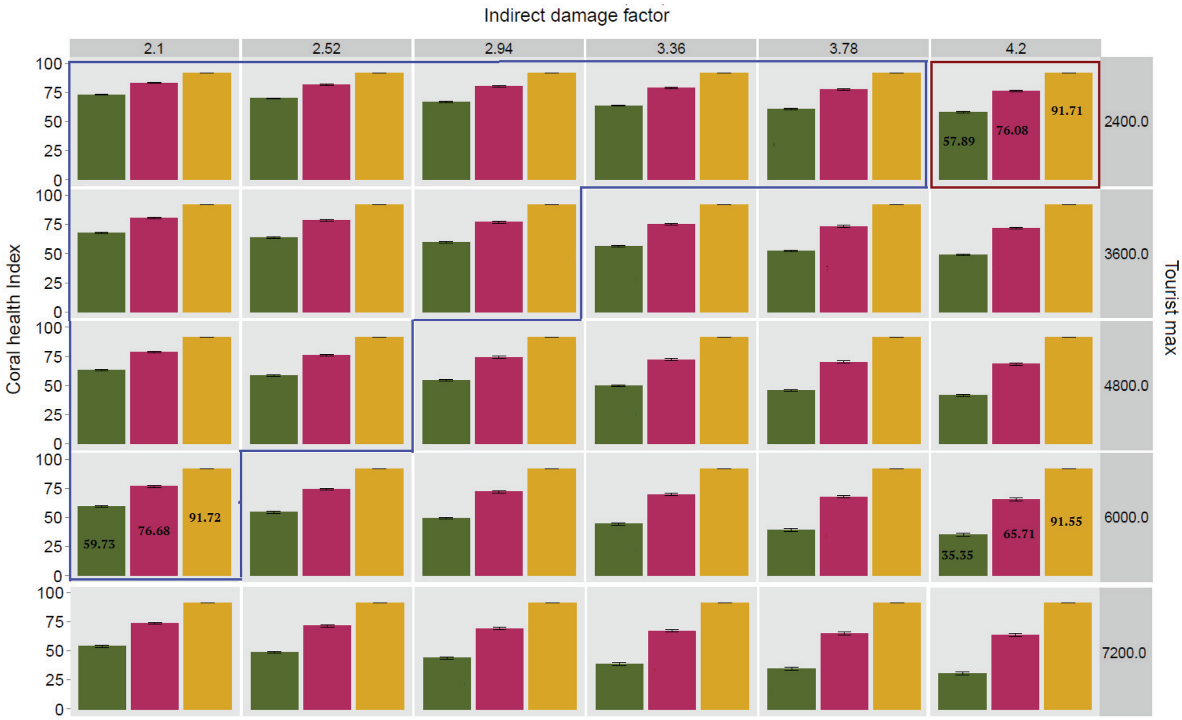


Figure 3.15: Coral health index response to different combinations of the tourist maximum and the indirect damage factor: Average coral health index of nearshore (green), medium distance (pink) and offshore (yellow) dive sites in the final simulation year. The standard configuration is outlined in red; the area outlined in blue encloses cases where the coral health index is higher than the standard configuration.

When measures to control the number of visitors are combined with measures to reduce land-based pollution (i.e. the indirect damage factor in the model), results indicate that reducing the indirect damage factor can help offset the negative impacts on coral health caused by increasing visitor numbers and improve coral health if visitor numbers remain the same (Fig. 3.15). If the management goal is to maintain the current coral health status, reducing indirect damage rate to half of the current level allows the tourist maximum to be increased by 250% compared to the configuration value, i.e.to 6000. Under these conditions (indirect damage factor = 2.1, tourist maximum = 6000) the coral health index at nearshore dive sites is 59.73 (SD = 1.6, n = 20), which is higher than the standard configuration value of 57.89 (SD = 1.26, n =20), with smaller improvements also seen at medium distance and offshore dive sites. Under the same scenario, the annual income of all dive schools increases by 262.5% (from 200 million Baht to 725 million Baht) in the final year of the simulation, as a result of a 145.5% increase in the number of annual visitors (from 110,000 to 270,000).

In summary, increasing the number of visitors results in degraded coral health. Unexpectedly, when the tourist maximum increases, no limits to dive school income and actual visitor numbers on Koh Tao were observed under the range of scenario conditions tested. However, other studies (e.g. Hawkins and Roberts 1997; Dixon et al. 2000) suggest that a threshold level for tourist numbers exists. When this threshold is exceeded, this can lead to collapse of the coral ecosystem and, consequently, a reduction in tourism. This is perhaps due to the fact that in KohTaoSim, there is no consideration of social acceptance of increased tourist numbers, or possible limits to infrastructure or accommodation development. Under this condition, it seems that dive school income and tourist numbers are positively correlated to the tourist maximum without limit. In the case of Koh Tao as simulated in KohTaoSim, when the tourist maximum increases above the configuration value (2400), the actual number of visitors increases more slowly than the increase in the tourist maximum, and the discrepancy between the two values increases. Thus no regulation of visitor numbers is required, as market competition self-regulates visitor numbers by limiting the incentives to install new capacity. Reducing the indirect damage factor (by constructing waste water plants or reforestation) is an efficient option that enables the current coral health status to be maintained while increasing tourist numbers and overall dive school income. While public education might be effective in changing the behavior of individual divers (Krieger and Chadwick 2012, Toyoshima and Nadaoka 2015), it is not effective in terms of maintaining or improving coral health. However, it could have a direct effect on the overall income of all dive schools, especially eco-dive schools, as environmental awareness increases the willingness of SCUBA divers to pay for more expensive eco-dive schools. Thus, for eco-dive schools, it makes sense to run public education programs as a means of increasing their individual incomes. The influence of NGO increases as the number of visitors increases. This allows more funding to be raised for conservation actions and public educational programs, thereby further increasing the pro-environmental rate among visitors. This kind of positive feedback loop resulting from an increase in environmental awareness has been documented also in Belize (Diedrich 2007) and Galapagos (Powell and Ham 2008), where visitors were found to have developed a sense of stewardship towards marine resources that was attributed to public education and awareness-raising programs.

3.3 Cases

In this section, summary results for two contrasting scenarios are presented. Under a ‘worst case’ scenario, a high level mass mortality event occurs every second year; under the ‘most likely’ scenario, a medium level mass mortality event occurs every 8 years. In each case, model runs were performed to assess the development of the Koh Tao SES (1) without tourism, (2) with tourism without eco-labeling, (3) with tourism with eco-labeling (standard configuration) (4) with tourism without eco-labeling and the level of indirect damage reduced by half; and (5) with tourism with eco-labeling and the pro-environmental rate set at 100%. These 5 alternative conditions are referred to as Cases 1 to 5 in the following sections.

Most likely case

Under the most likely case scenario, coral health remains good if there is no tourism (Case 1), despite the occurrence of a medium level mass mortality event every 7 years (Fig 3.16a). There are no significant differences of coral health or dive pressure between the monsoon side and non-monsoon side of the island ($T_{(8)}$=1.0509, p=0.324). A significant variation of dive pressure ($F_{(4,20)}$=10.716, p=0.0001) and coral health ($F_{(4,20)}$=4.507, p=0.0093) at sites classified by type of use (snorkeler, open water, advanced etc.).

Open water (O), advanced & open water (A&O) dive sites are the most frequently chosen dive destinations under this scenario. At sites that are heavily dived, the introduction of an eco-labeling system reduces the dive pressure by 1.5% at advanced & open water dive sites and by 3.4% at open water dive sites (Case 2 vs. Case 3, Fig 3.18b). At the same time, the coral health index in the final simulation year increases by 0.98% (from 50.1 to 51.16) at advanced & open water dive sites and by 1% (from 43.77 to 44.22) at open water dive sites (Case 2 vs. Case 3, Fig 3.16a). When, in addition to eco-labeling, public education programs raise the pro-environmental rate among visitors to 100%, dive pressure is significantly reduced: specifically, by 3.1% at advanced & open water dive sites and 8.3% at open water dive sites (Case 3 vs. Case 5, Fig 3.16b). At the same time, the coral health index in the final simulation year will increase by 2.8% (from 50.1 to 52.09) at advanced & open water dive sites and by 3% (from 43.77 to 45.12) at open water dive sites (Case 3 vs. Case 5, Fig.3.16a). If the indirect damage factor is reduced by half, the coral health factor increases at all types of dive sites, by an average of 22.2 % (SD = 4.5%, n = 20, Fig.3.16a). However, the sites that are already heavily dived may face even higher dive pressure; the dive pressure increases by 6.4% at advanced & open water dive sites and 2.1% at open water dive sites (Case 4 vs. Case 5, Fig 3.16b).

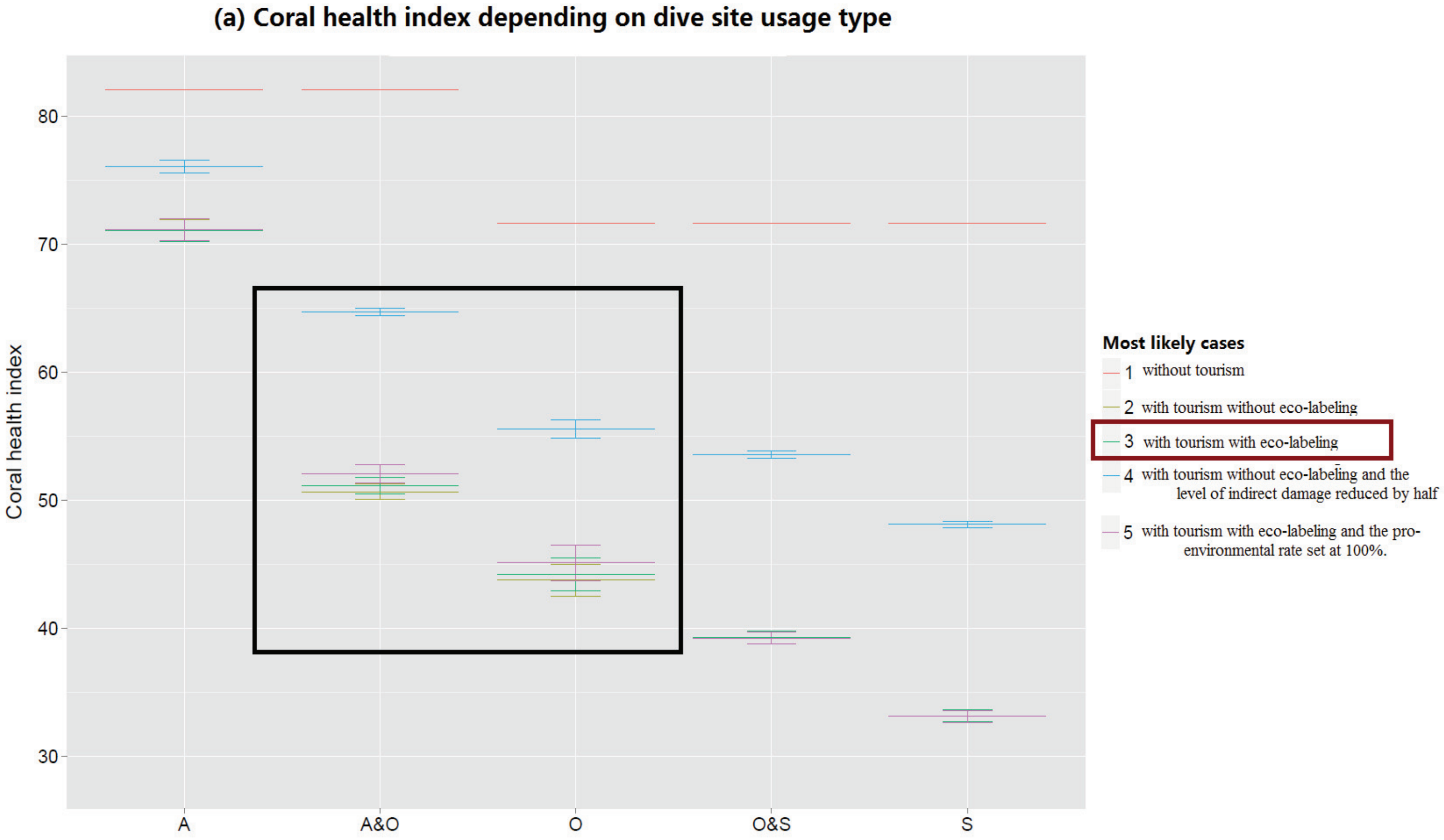

(a) Coral health index depending on dive site usage type

Figure 3.16: Coral health index and dive pressure response to different most likely scenario situations: with medium level mass mortality events occur every 7 years: (a) **a**verage **c**oral health index in the last year of simulation. In each case results are grouped by type of dive site (A: advanced SCUBA; O: open water SCUBA; S: snorkeling) and shown for five alternative cases: 1: without tourism; 2: with tourism without eco-labeling; 3: with tourism and eco-labeling; 4: with tourism without eco-labeling and indirect damage reduced by half; 5: with tourism with eco-labeling and the pro-environmental rate increased to 100%. Long horizontal lines show means and short horizontal lines indicate standard errors. Black square closes the situation where eco-labeling and public education improved coral health index. The standard configuration situation is outline in red.

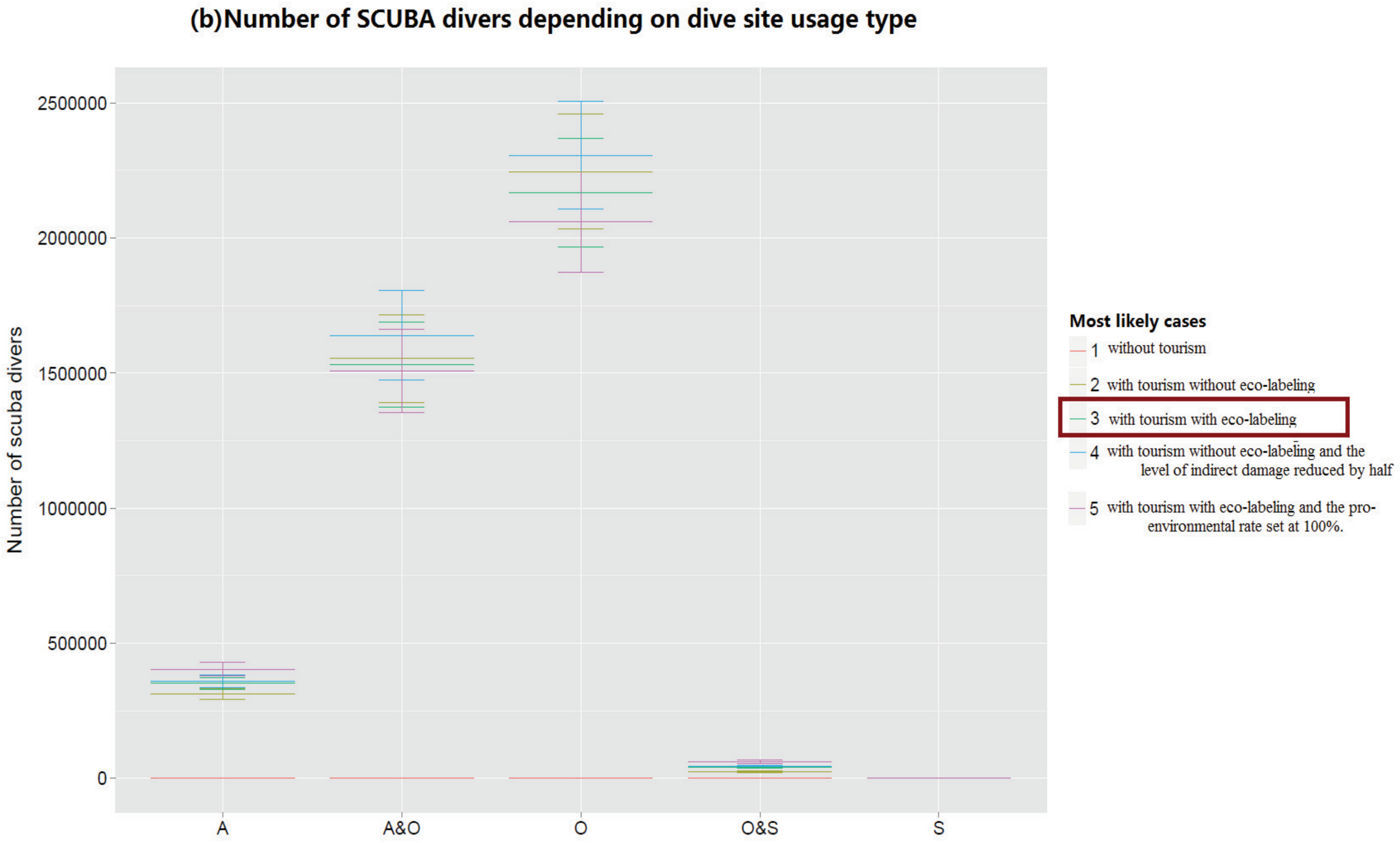

(b)Number of SCUBA divers depending on dive site usage type

Figure 3.16: Coral health index and dive pressure response to different most likely scenario situations: with medium level mass mortality events occur every 7 years: (b) accumulated numbers of SCUBA divers number at dive sites over the entire simulation period In each case results are grouped by type of dive site (A: advanced SCUBA; O: open water SCUBA; S: snorkeling) and shown for five alternative cases: 1: without tourism; 2: with tourism without eco-labeling; 3: with tourism and eco-labeling; 4: with tourism without eco-labeling and indirect damage reduced by half; 5: with tourism with eco-labeling and the pro-environmental rate increased to 100%. Long horizontal lines show means and short horizontal lines indicate standard errors. The standard configuration situation is outline in red.

When the coral health status is improved, the number of divers and snorkelers increases while the number of sightseers decreases. In general, Koh Tao Island remains a dive tourism destination under the most likely case scenario. Implementation of eco-labeling and public education will have no influence on visitor numbers or the type of visitor (comparison of Cases 2, 3 and 5, Fig.3.17). But a decrease in indirect damage will increase the number of SCUBA divers by 6.3%, and, particularly, increase the number snorkelers by 32.6%, while reducing the number of sightseers by 3.7% (Fig.3.17).

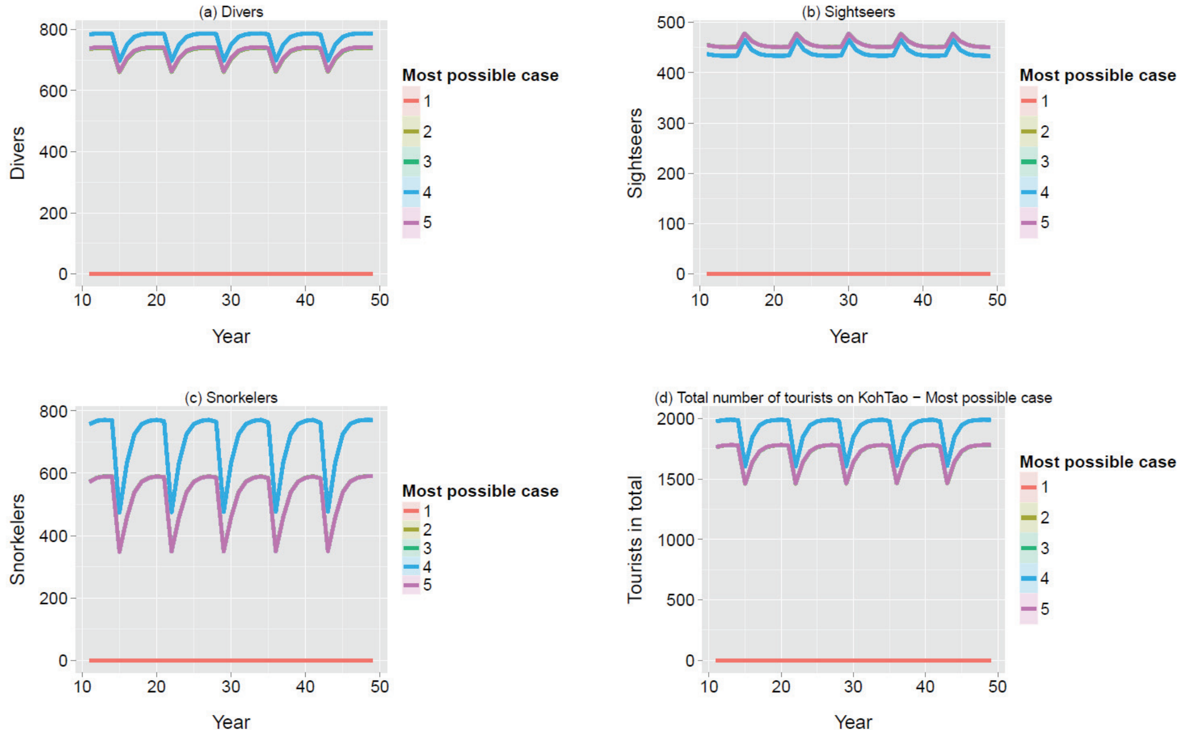
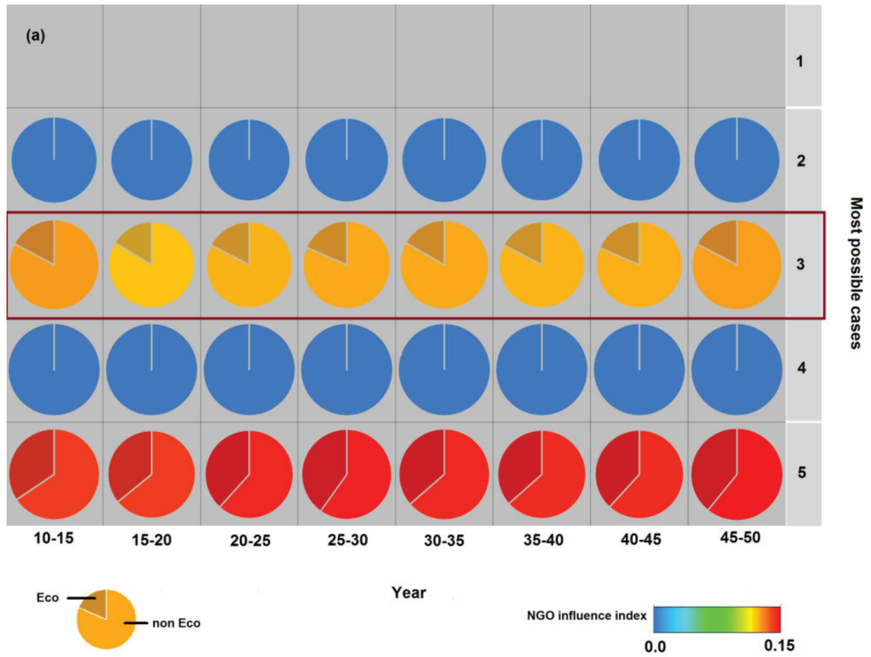


Figure 3.17: Changes in tourists number under different most likely scenario situations: with medium level mass mortality events occur every 7 years: daily numbers of (a) SCUBA divers (b) sightseers (c) snorkelers and (d) all tourists on Koh Tao for five alternative cases: 1: without tourism; 2: with tourism without eco-labeling; 3: with tourism and eco-labeling; 4: with tourism without eco-labeling and indirect damage reduced by half; 5: with tourism with eco-labeling and the pro-environmental rate increased to 100. In this figure, line 2, 3 and 4 overlap.

When income is considered, results show that implementation of eco-labeling increases the overall income of all dive schools (Fig. 3.18a). Specifically, the average annual income of all dive schools increases from 155 million Baht (n = 50, SD = 4.57E+06, Case 2) to 164 million Baht (n = 50, SD = 4.55E+06, Case 3). When eco-labeling is combined with successful public education (pro-environmental rate = 100%, Case 5), the average annual income of all dive schools increases to 169 million Baht (n = 50, SD = 4.06E+06). On the other hand, without eco-labeling, when indirect damage is halved (Case 4) the average annual income of all dive schools increases to 185 million Baht (n = 50, SD = 4.98E+06). A comparison of Cases 3 and 5 shows that when the pro-environmental rate is higher, the NGO influence index also increases. This is consistent with previous simulations. This increases the income of eco-dive schools. However, overall incomes of non-eco dive schools remain higher than those of eco-dive schools (Fig.3.18a). Examination of the dynamics of dive school incomes over the entire simulation period reveals that, while total incomes broadly follow coral health, the distribution of incomes between eco and non-eco dive schools is highly variable and dependent on random processes, as shown by the very large standard errors in Fig. 3.20b. Under the most likely scenario, an increased pro-environmental rate also increases the possibility that eco-dive schools will have higher incomes that non-eco dive schools, particularly at the start of the simulation period (Case 5, Fig. 3.18b). However, non-eco dive schools still generate better economic returns than eco-dive schools over the long run.



(b) Temporal dynamic of average dive school annual income

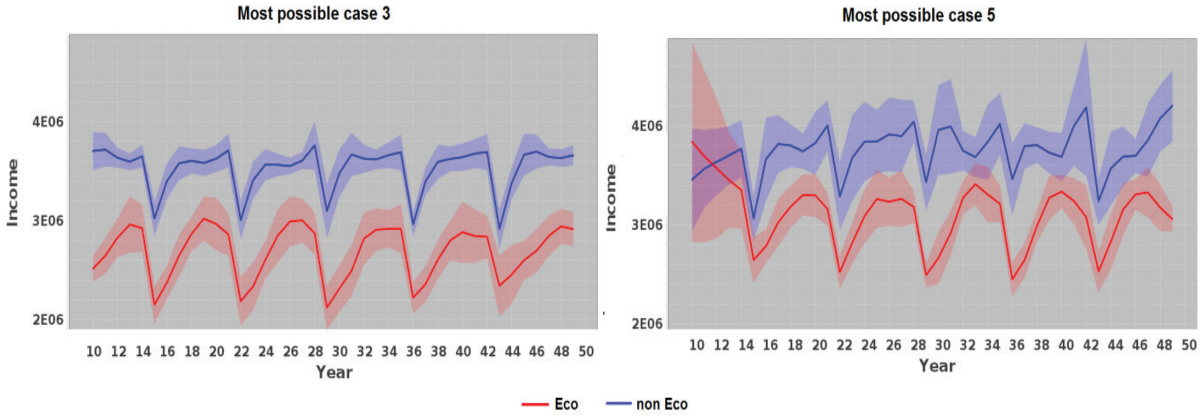


Figure 3.18: Changes in dive schools' income and NGO influence index under different most likely scenario situations: with medium level mass mortality events occur every 7 years: (a) The average annual income of all dive schools in each time period (size of pie), NGO influence index (color of pie), and distribution of income between eco and non-eco dive schools (segments of pie) for five alternative cases: 1: without tourism; 2: with tourism without eco-labeling; 3: with tourism and eco-labeling; 4: with tourism without eco-labeling and indirect damage reduced by half; 5: with tourism with eco-labeling and the pro-environmental rate increased to 100. The standard configuration situation is outline in red. (b) Evolution of incomes of eco and non-eco dive schools over the entire simulation period for Case 3 (left) and Case 5 (right). The lines show means while the shaded areas indicate standard errors.

Worst case

For the worst case scenario, the coral health does not drop to zero at any type of dive site when tourism is non-existent (Case 1, Fig. 3.19a). However at sites near the coast (open water, open water & snorkeling or snorkeling sites) the average value of coral health index in the final simulation year will be very low, at 19.24 (n = 11, SD = 0). If tourism is practiced (Cases 2 to 5), these dive sites will not survive, since the coral health index will fall to zero, even when indirect damage is reduced by a half (Fig. 3.19a). Correspondingly, advanced & open water dive sites are the most frequently chosen dive destinations under this scenario (Fig3.21b). With implementation of eco-labeling (Case 3, Fig.3.19b), dive pressure at these sites is reduced by 7.3%. If the pro-environmental rate is increased to 100% (Case 5, Fig.3.21b), dive pressure is reduced by 15.9%. These measures also lead to an increase in the coral health index by 2.3% for Case 3 and 7% for Case 5 (Fig.3.21a). Reducing indirect damage increases the coral health index (Case 4 vs. Case 3), specifically by 23% at advanced and open-water dives sites and by 5.8% at advanced dive sites (Fig. 3.21 a).

Under this scenario, the overall income of all dive schools increases with the implementation of eco-labelling (Case 2 vs. Case 3, Fig. 3.20a). Specifically, the annual income of all dive schools increases from 82.9 million Baht (n = 50, SD = 2.72E+06) without eco-labeling to 91 million Baht (n = 50, SD = 2.6+06) when eco-labeling is introduced (Case 3). When eco-labeling is combined with a successful public education (pro-environmental rate = 100%; Case 5, Fig.3.20a), the average annual income of all dive schools increases to 98 million Baht (n = 50, SD = 4.6E+06).This is similar to the result for Case 4, i.e. where there is no eco-labeling, but if indirect damage is reduced by half: in this case, the average annual income of all dive schools is 97.7 million Baht (n = 50, SD = 4.98E+06). Similar to the most likely case scenario, comparison of Cases 3 and 5 shows that when the pro-environmental rate is higher, the NGO influence index also increases, and with it the overall profitability of eco dive schools (Fig.3.20a). Examination of the dynamics of dive school incomes over the entire simulation period reveals that, as in the case of the most likely scenario, total incomes broadly follow coral health; the more rapid fluctuations shown in Fig 3.20b compared to Fig. 3.18b correspond to the increased frequency of mass mortality events. Overall non-eco dive schools still generate better economic returns than eco-dive schools in the long term. However the effects of an increased pro-environmental rate (Case 3 vs. Case 5, Fig 3.20b) are less marked than under the most likely scenario, and the income of eco-dive schools could (with a low probability) match or even exceed that of non-eco dive schools with or without an increased pro-environmental rate, and later on in the simulation period as well as at the start (Fig. 3.20b).

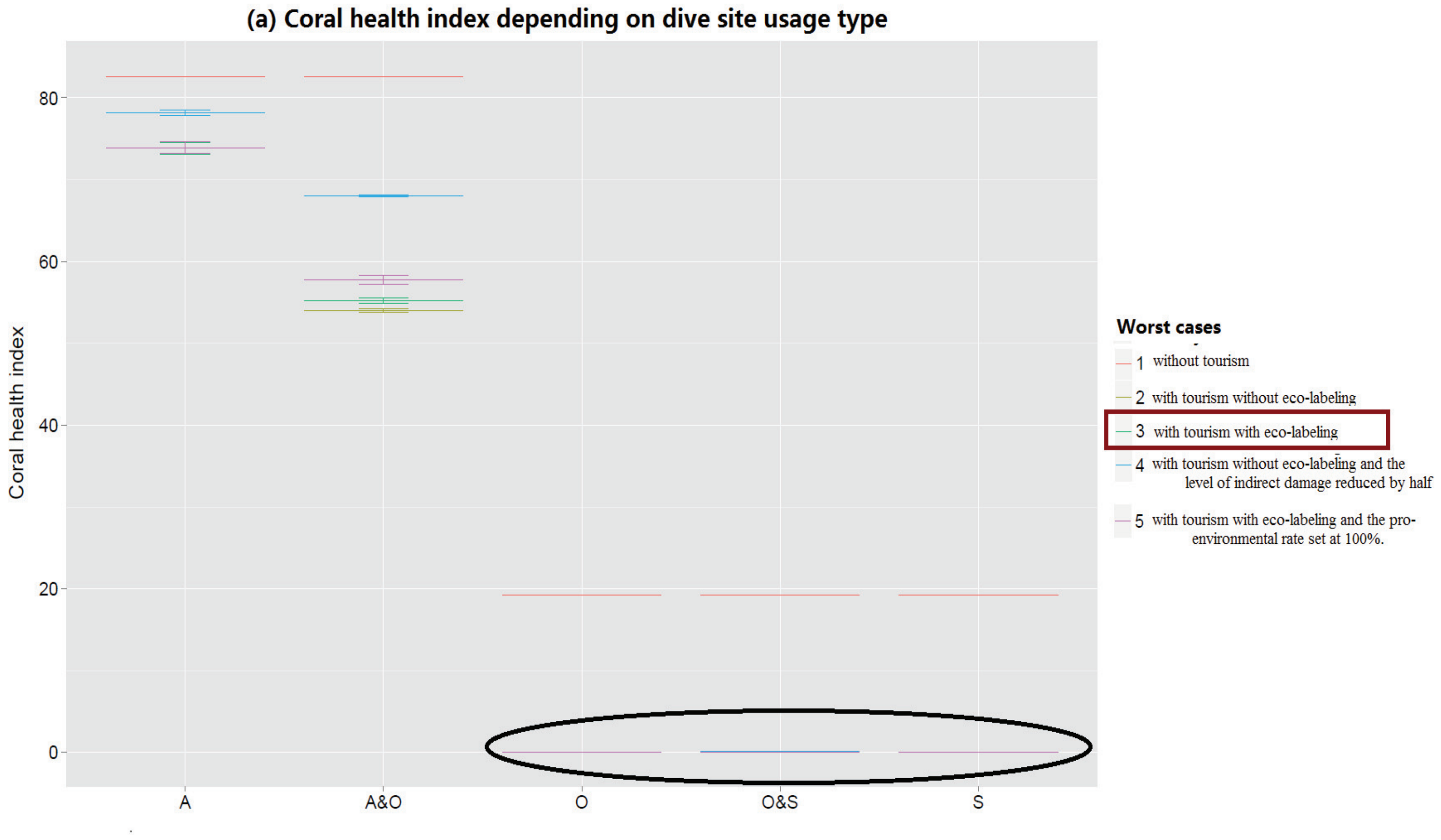


Figure 3.19: Coral health index and dive pressure response to different worst case scenario situations: with high level mass mortality events occur every 2 years: (a) average coral health index in the final simulation. In each case results are grouped by type of dive site (A: advanced SCUBA; O: open water SCUBA; S: snorkeling) and shown for five alternative cases: 1: without tourism; 2: with tourism without eco-labeling; 3: with tourism and eco-labeling; 4: with tourism without eco-labeling and indirect damage reduced by half; 5: with tourism with eco-labeling and the pro-environmental rate increased to 100%. Long horizontal lines show means and short horizontal lines indicate standard deviations. The black oval encloses cases where the coral health index falls to zero. The standard configuration situation is outline in red.

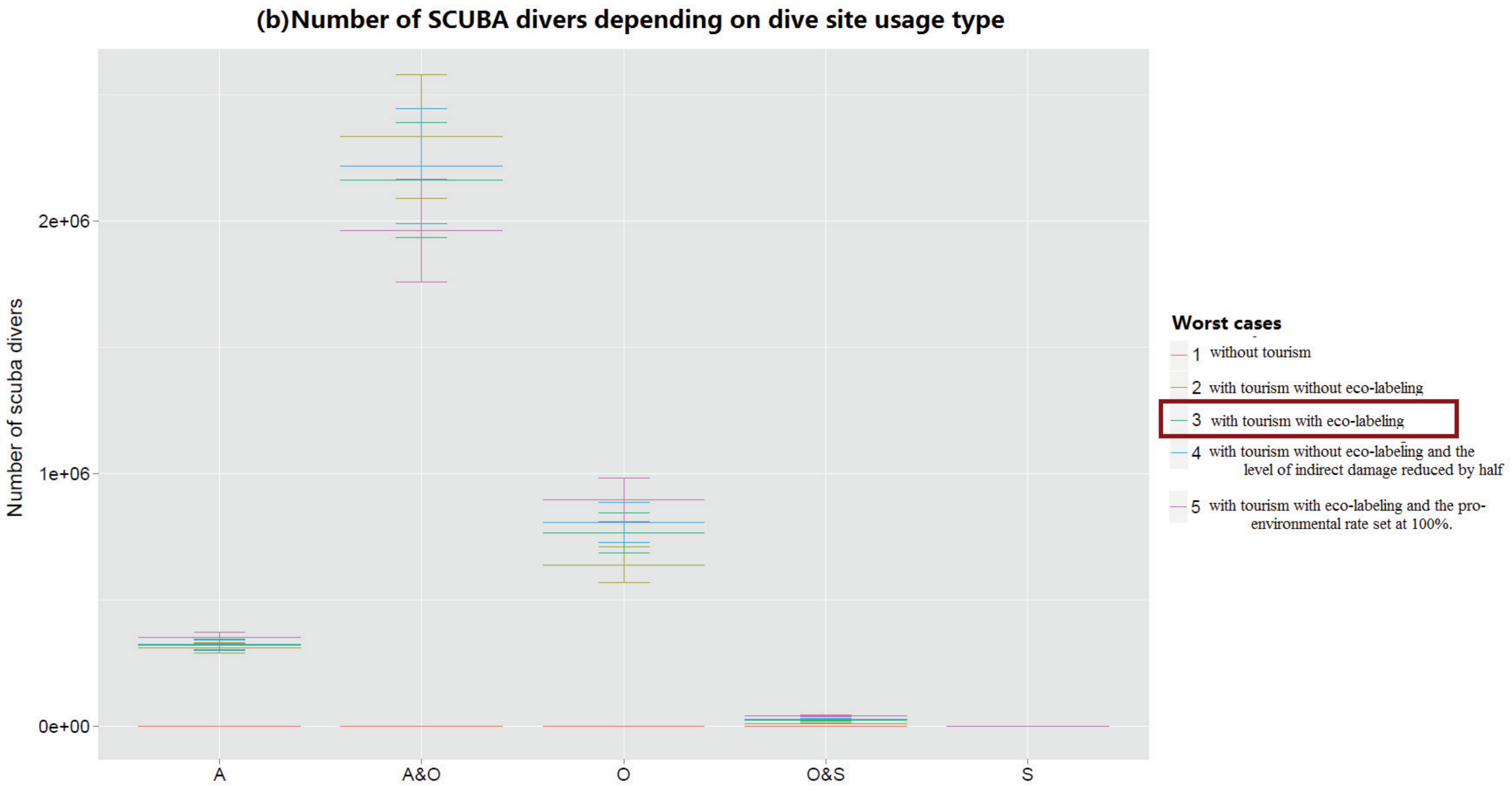
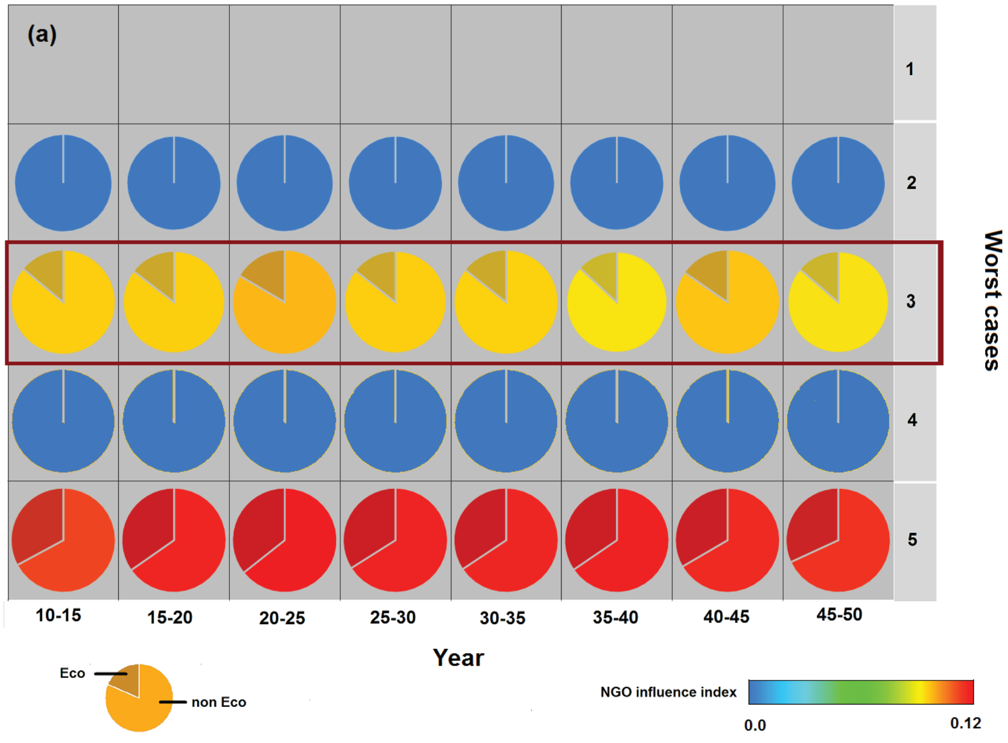


Figure 3.19: Coral health index and dive pressure response to different worst case scenario situations: with high level mass mortality events occur every 2 years: (b) accumulated total SCUBA divers number over the entire simulation period. In each case results are grouped by type of dive site (A: advanced SCUBA; O: open water SCUBA; S: snorkeling) and shown for five alternative cases: 1: without tourism; 2: with tourism without eco-labeling; 3: with tourism and eco-labeling; 4: with tourism without eco-labeling and indirect damage reduced by half; 5: with tourism with eco-labeling and the pro-environmental rate increased to 100%. Long horizontal lines show means and short horizontal lines indicate standard deviations. The standard configuration situation is outline in red.



(b) Temporal dynamic of average dive school annual income

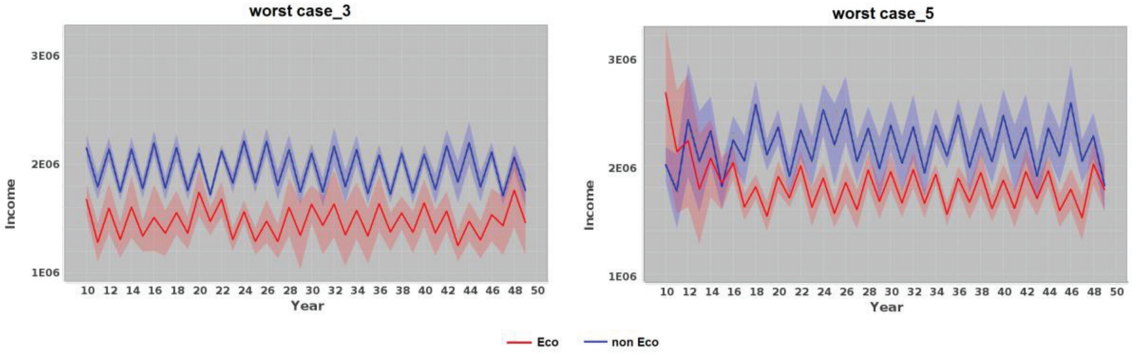


Figure 3.20: Changes in dive schools' income and NGO influence index under different worst case scenario situations: with high level mass mortality events occur every 2 years: (a) The average annual income of all dive schools in each time period (size of pie), NGO influence index (color of pie), and distribution of income between eco and non-eco dive schools (segments of pie) for five alternative cases: 1: without tourism; 2: with tourism without eco-labeling; 3: with tourism and eco-labeling; 4: with tourism without eco-labeling and indirect damage reduced by half; 5: with tourism with eco-labeling and the pro-environmental rate increased to 100. The standard configuration situation is outline in red. (b) Evolution of incomes of eco and non-eco dive schools over the entire simulation period for Case 3 (left) and Case 5 (right). The lines show means while the shaded areas indicate standard error.

In the worst case scenario, eco-labeling or public education has little effect on the number of tourists (Fig. 3.21). In the figure, Cases 2, 3 and 5 are almost overlapping, signifying little change. The overall number of tourists decreases only slightly over the simulation time. The type of tourism, however, changes dramatically: with degradation of coral occurring especially at snorkeling sites (Fig.3.19a), snorkelers will disappear from Koh Tao. In this case, eco-labelling and, especially, measures to reduce indirect damage (Case 4, Fig. 3.21d) slow down the process. Snorkelers still disappear, but after a longer time.

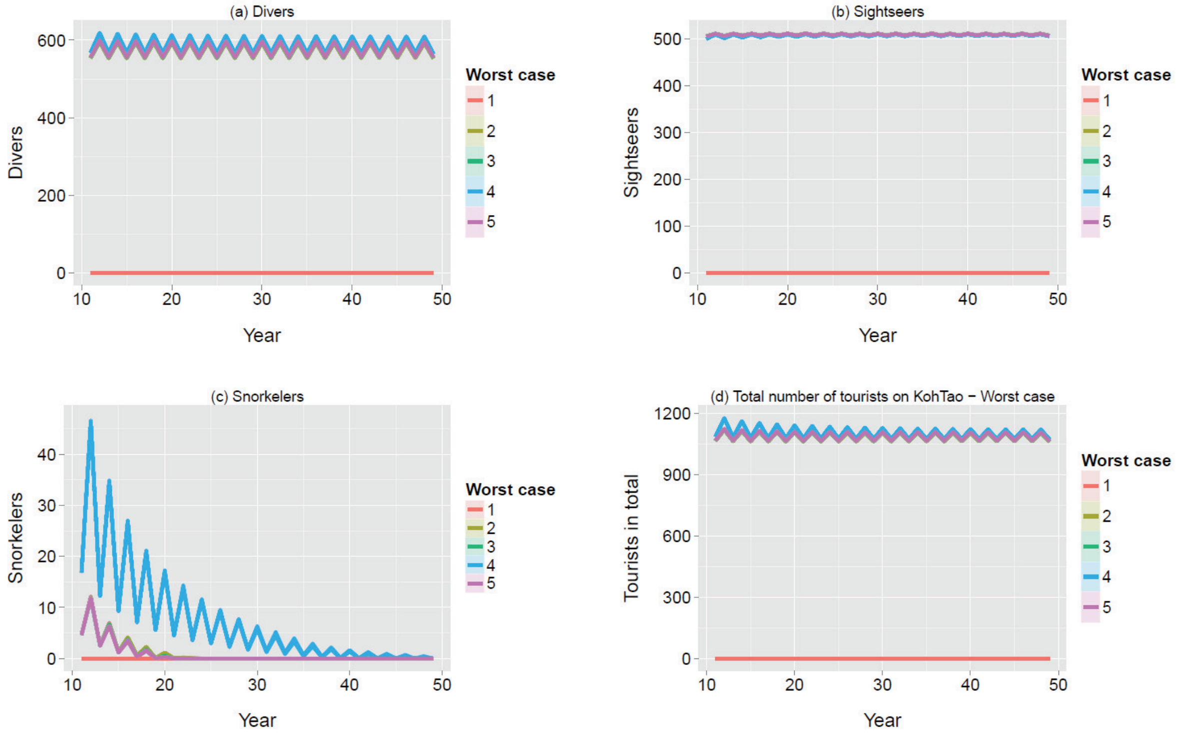


Figure 3.21: Changes in tourists number under different worst case scenario situations: with high level mass mortality events occur every 2 years: daily numbers of (a) SCUBA divers (b) sightseers (c) snorkelers and (d) all tourists on Koh Tao for five alternative cases: 1: without tourism; 2: with tourism without eco-labeling; 3: with tourism and eco-labeling; 4: with tourism without eco-labeling and indirect damage reduced by half; 5: with tourism with eco-labeling and the pro-environmental rate increased to 100.

In conclusion, besides the clear influence of mass mortality events, tourism development as shown in the scenarios could lead to further coral degradation at a local level. This is particularly true for the dive sites facing high level of local stress from tourism. This aggravating effect of local stress, amplifying the effects of global stress, is more obvious where reefs are close to the coastline or used as open water or snorkeling sites (and are therefore affected by high levels of indirect and direct damage, respectively). Reducing the indirect damage factor can be effective in preventing adverse effects on coral health from tourism activities when the mass mortality events are infrequent and their impact is not very severe. When the global stressors are extreme (the worst case scenario), reducing indirect damage has a limited effect: as nearshore dive sites are still destroyed and the improvement of offshore dive sites is smaller compared to the most likely case scenario.

Eco-labeling and the improvement of environmental awareness among tourists enhance the health status of corals, but only at frequently used dive sites. Implementation of eco-labeling and environmental education programs and reducing indirect damage can all help increase total income of dive schools. But the mechanisms involved are different. As indirect damage is reduced, coral health improves and this attracts more divers. This effect is apparent in the increases in numbers of tourists (Case 4, Fig 3.17) and dive school income (Case 4, Fig. 3.18) for the most like case scenario. By contrast, eco-labeling and public education have little effect on tourist numbers (Cases 3 and 5, Figs. 3.17 and 3.21). Rather, they affect the willingness of SCUBA divers to pay for extra pro-environmental practices, which also increases the overall income of dive schools and especially of eco-labelled dive schools (Cases 3 and 5, Figs. 3.18 and 3.20).

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CHAPTER IV SYNTHESIS

4.1 Understanding SES dynamics

4.1.1 Key drivers of coral degradation: Global vs. local stressors

Debates about the causes of coral reef degradation tend to focus on either global or local stressors; few studies consider interactions of stressors across different scales (Pandolfi et al. 2005, Knowlton and Jackson 2008). But with the help of KohTaoSim, all kinds of stressors, global and local, can be isolated and tested in different combinations. Results from the different testing scenarios (i.e. the mass mortality, worst case and most likely case scenarios) show clearly that patterns of development of coral health are mainly shaped by mass mortality events (Figs. 3.4, 3.16 and 3.19). At the scale of the coral reef community, mass mortality events are the most powerful influencing factor. This phenomenon has been reported across coral systems worldwide (Smith and Buddemeier 1992, Aronson and Precht 2006, Manzello 2010, Edmunds et al. 2013). In the case of Koh Tao, historical severe coral losses are also very likely linked to global or local coral bleaching events (Yeemin et al. 2001, Tun et al. 2004, Chavanich et al. 2012). In KohTaoSim, comparison of the changes in the coral health index loss caused by incremental changes (positive or negative) in single parameters, shows that the effects of global stressors are larger than those of local stressors and mitigating factors, such as indirect damage, visitor numbers, direct damage or environmental awareness among tourists (Table 4.1). Clearly this result is the effect of assumptions and algorithms built into the model; these in turn largely reflect the empirical results and the informed opinions of local stakeholders. KohTaoSim shows that under these assumptions, global stressors are the main driver of coral degradation.

Table 4.1: Effects of changing parameter values at Koh Tao, as modeled by KohTaoSim. For each parameter, the table shows the average change of coral health, dive school income, and visitor numbers from 10% parameter value shift. Arrows indicate direction of change. Percentages show the magnitude of change in comparison with the standard configuration setting.

Testing parameter	**Effects on Koh Tao SES**		
	Coral health index	Total income of dive schools	Total daily visitor numbers
Coral health index growth rate (↓)	6.9% (↓)	3.7% (↓)	3.25% (↓)
Indirect damage (↓)	5.3% (↑)	2.1% (↑)	2.3 % (↑)
Tourist maximum (↑)	4.4% (↓)	12.46% (↑)	6.1% (↑)
Direct damage (↓)	0.76% (↑)	↔	↔
Pro-environmental rate(↑)	↔	0.35 % (↑)	↔

Results of the worst case, most likely case and mass mortality scenarios show that dive sites with high local stress (both indirect and direct) react more sensitively to global stress. For example, in the worst case scenario, the coral health index at open water and/or snorkeling sites falls to zero as long as tourism is included as a factor in the model run (Fig. 3.19). In response to changes in the strength and frequency of mass mortality events, nearshore sites with higher local stress from tourism are more severely affected by same level of global stress than offshore sites (Fig. 3.4): local stress exacerbates the global stress. Similar arguments are developed in discussions of coral ecology and studies of coral reef management (Pandolfi et al. 2005, Keller et al. 2009). While global stressors are the principal driver of coral reef degradation, improved understanding of the local drivers on coral lost is also very important for the management and protection of coral reefs.

Comparison of the effects of local stressors (and mitigating factors) (Case 4 vs. Cases 3 and 5 in Figs. 3.16 and 3.19; Table 4.1) shows that indirect damage caused by pollution outflows from the island to the marine environment associated with tourism development are much more influential than direct damage to corals caused by divers (or the mitigating effects of increasing the pro-environmental rate and the eco-labeling system). Direct damage caused by divers influences coral health only at heavily dived sites. This was also found to be the case in several previous studies (Tratalos and Austin 2001, Barker and Roberts 2004, Hasler and Ott 2008). Even at heavily dived sites, the effect of damage caused by divers is limited compared to indirect damage or global stressors, as shown in the worst case scenario where coral reefs at open water and/or snorkeling dive sites die out as a result of pollution and mass mortality events even with a shift in dive behavior. The results of the public education scenario (Fig. 3.19) lead to a similar conclusion. Increasing the pro-environmental rate leads to no obvious improvement in the coral health index. In the most likely case scenario, it has no obvious effect on coral health at sites that are not heavily used (Fig. 3.16).

4.1.2 Driving factors in social-economic perspective

In general, results of this study show that the better coral health is, the more tourists will visit the island, thereby increasing community income in the majority of the cases. Thus, all the driving factors with an influence on coral health will indirectly affect the economic benefits of tourism development on Koh Tao.

However, the parameter tourist maximum (reflecting transportation capacity) is the principal driving factor with a direct effect on visitor numbers and, especially, community income. As illustrated in Table 4.1, an increase in the value of this parameter leads directly to a dramatic increase in visitor numbers on KohTao and the income of all dive schools. This contributes to the degradation of coral reefs as a result of increased pollution and direct damage. However, when eco-labelling is implemented jointly with public education, this can help reduce dive pressure, which in turn will improve the diving experience and lead to higher levels of satisfaction among SCUBA divers. Most importantly, the higher prices charged by dive schools that buy in to the eco-labeling scheme will increase the calculated total income of all dive schools.

4.2 Sustainable management suggestions

Coral-based or coral-associated tourism contributes more than 15% to local economies in more than 20 countries and territories (Burke et al. 2011). Dive tourism does not only brings economic benefits (Brander et al. 2007); it also acts as a disincentive to other economic uses of coastal areas such as intensive aquaculture that might threaten coral reef health (Cater

2010), and can even promote marine conservation (Diedrich 2007). However, as dive tourism develops, it also incurs substantial ecological costs and to some extent, also social-economic costs. Intensively used dive destinations such as the Red Sea (Zakai and Chadwickfurman 2002) and the Maldives (Goffredo et al. 2007), have experienced negative effects from dive tourism development that have led to concerns over the future of reef-based dive tourism. Sustainable tourism management aims to minimize the negative effects of tourism and secure the sustainability of costal resources and tourism industry through planned development or adoption of operational procedures based on the principle of sustainability (Bramwell 1996, Buckley 2001). There is increased interest among researchers and managers in the development, with the involvement of local stakeholders, of integrated management plans based on an in-depth understanding of coral-based dive tourism from a social-ecological system (SES) perspective (Zagonari 2008, Wongthong and Harvey 2014).

In this study, an ABM, KohTaoSim, was developed and tested basing on inputs from scientific research and with involvement of local resource users throughout the entire processes. The model was used to explore the dynamics of the SES under different scenarios and also to test the effects of management approaches suggested by local stakeholders. Since local management plans will not reduce global stressors affecting coral reefs, the aims of a sustainable management plan for Koh Tao should be (1) to prevent further coral reef degradation by increasing coral ecosystem resilience to global stressors and thereby (2) to maintain or increase community economic income in a long term. The following sections present the outline of such a plan for Koh Tao dive tourism development, based on the new knowledge generated by KohTaoSim. Since the governmental capacity to influence development on Koh Tao is weak, priority is given to community oriented approaches and voluntary management regulations as recommended by previous studies on Koh Tao (Worachananant et al. 2008, Wongthong and Harvey 2014).

It should be stressed at the outset that all the simulation results presented are a consequence of assumptions and algorithms built into the model. While every effort was made to incorporate the knowledge and opinions of scientific and lay experts into the model, it is still a highly simplified and necessarily incomplete representation of the real world social ecological system. For example, this study focuses on the effects of implementation and does not consider wider issues such as economic efficiency or the extent to which the management measures suggested are acceptable to local stakeholders and likely to receive their support. With this proviso, the following suggestions are offered for further discussion among resource users and institutions to assist decision-making on appropriate measures to coral-based dive tourism on Koh Tao - and definitely not as predictions of what might or might not happen if a certain course of action were followed.

4.2.1 Ecological instruments

Artificial dive site

Although the construction of an artificial dive site will not necessarily lead directly to an improvement of overall coral health around Koh Tao, model results suggest it is likely to have a positive effect on the income of dive schools, as well as reducing dive pressure at natural dive sites (Fig. 3.10d & e). In this study, only one additional artificial dive-site was tested at a time. However, it could be imagined that establishing more artificial dive sites in simulation would multiply the effects. Thus the implementation of artificial dive sites could be a very good option for sustainable tourism development on Koh Tao. If investment in artificial dive sites is being considered, the findings suggest that these should be constructed on the west side of the island, which is less affected by the monsoon and therefore accessible to divers throughout the year. In general, locations between Sairee and Ao Mae Haad appear to be optimal (Fig. 1.2a). Ideally an artificial dive site should be located at least 500 m away from the coast in order to avoid indirect damage (i.e. from pollution inflows from coastal areas) that could make the artificial site less attractive to divers. However, transport costs for the dive schools are also important, and if an artificial dive site is located too far away from the coast its cost efficiency will be reduced. Therefore, a location less than 2000 meters from the coastline is recommendable. Furthermore, model results suggest that: from an economic perspective, considering the high density of dive schools in the south-west part of the island, this area also offers a favorable location for artificial dive sites, as transportation costs would be low for nearby dive schools.

4.2.2 Control tools

Visitor number control

According to the results from KohTaoSim, control on the number of tourists, through limiting the capacity of tourism facilities or imposing direct limits on numbers of tourists, might not be necessary. As previously discussed in the section on the corresponding model scenario, when the maximum number of visitors (based on transportation capacity) rises above the current level, the actual number of visitors will increase more slowly than the capacity of the island to receive visitors. Empty places on boats and unoccupied hotel rooms will act as a disincentive for the further development of transportation and accommodation facilities. Thus the number of visitors is controlled by means of self-regulating, market-based mechanisms. It should be emphasized that this result is based on assumptions and algorithms that are built in to KohTaoSim, developed in consultation with local stakeholders. However this recommendation should be treated with caution as it contradicts the results of some other studies, as noted above.

Coastal pollution control

Koh Tao is increasingly well-known as a tourism destination in Thailand, and there is a huge potential for a rapid increase in the number of visitors in the near future. The rise in the number of tourists could have severe negative impacts on coral ecosystems due to increased pollution inflows from coastal tourism facilities into the marine environment. Measures to control pollution inflows are a very effective ways to mitigate the negative impact of increasing visitor numbers, as evidenced by results of the corresponding simulations (Fig. 3.17). Waste water treatment (to reduce nutrient inflows) and reforestation (to reduce sediment and nutrient inflows) are essential and should be prioritized in Koh Tao as part of any strategy for sustainable development.

4.2.3 Voluntary instruments

Eco-labeling

Eco-labeling as a marketing tool for the promotion of pro-environmental practices by the tourism industry can be expected to influence preferences of consumers. This may lead to pro-environmental dive schools becoming more competitive and indirectly contribute to improved coral conservation. However, in all scenarios tested using KohTaoSim, the impact on coral conservation from eco-labeling is very limited. At most it will have limited positive effects at heavily dived sites. Economic benefits provide the principal incentive to sign up to eco-labeling schemes in the early stages of eco-tourism development. But in the long run, due to the higher costs of eco-labeling and as the number of eco-labeled schools grows, this economic advantage is not maintained. On the other hand, the reduction on dive pressure at busy dive sites is a positive outcome of eco-labeling, through its effects on the criteria used by dive schools for the selection of dive sites. This in turn may enhance the dive experience and increase satisfaction levels among SCUBA divers on Koh Tao. Furthermore, eco-labeling generates incomes for the NGO Save Koh Tao and thereby increases its influence. For the case of Koh Tao, this is important because the NGO is actually in charge of conservation measures on the island, where the presence of government agencies is minimal and their capacity for action is very low. The eco-labeling scheme run by Save Koh Tao is working well and should further be encouraged and promoted despite its limited direct effects on the reef ecosystem.

Public environmental education

Raising public awareness of environmental issues must be considered as a fundamental component of sustainable reef-based dive tourism development. It is not necessarily the case that implementation of awareness-raising measures such as pre-dive educational briefings, training in buoyancy control when diving in natural reefs, and closer underwater supervision of smaller dive groups etc. will have a direct effect on overall coral health. Most importantly, public education can ensure that all stakeholders are aware of the potential impacts of dive tourism activities and understand the importance of sustainable tourism management. Measures aimed at enhancing the sustainability of dive tourism can only be implemented effectively if local resource users are brought on board (Glaser et al. 2010, Wongthong and Harvey 2014). Thus awareness raising campaigns need to target all those living and working on the island as well as those directly involved in dive tourism.

4.3 Major findings and advances for SES analysis and sustainable management

Natural resource management (such as coral-based dive tourism management) requires a systems-based approach towards understanding the complex issues involved and should take account of both ecological and social dimensions (Forst 2009, Ferrol-Schulte et al. 2013). Working in one discipline is already complex; working in more than one discipline adds a further layer of complexity. In particular, it is easy to overlook factors that may be important for research and/or management outcomes. In this respect transdisciplinary SES approaches that incorporate local knowledge and stakeholder perspectives can be very helpful. However, the practical application of SES analysis, and translation of the resulting transdisciplinary knowledge into implementable management measures are still challenging and represent a daunting task (Glaser et al. 2010).

Drawing on the development of computer knowledge and power, alongside traditional mathematical models (applied mainly in natural science) and classic social economic empirical approaches (applied mainly in social science), agent-based models are widely recognized as having a high potential for the simulation of complex social-ecological systems and as a management tool, not least because this method presents its results in a form that can be easily communicated with stakeholders (Janssen and Ostrom 2006, Worrapimphong et al. 2010, Glaser 2012, Rounsevell et al. 2012, Schlüter et al. 2012). For this research, ABM was an appropriate option for SES analysis and an input to sustainable management for a number of reasons: Firstly, computer-supported analysis was required to capture the complexity of the situation, and integrate its spatial and temporal dimensions. Non-linear and non-equilibrium system dynamics often cannot be captured and analyzed by analytic mathematical models; this can be done using an ABM. Secondly, the ABM provides an appropriate platform for analysis of different types of data generated by empirical studies (in the classical social science tradition) and for displaying the results. Thirdly, the freedom to define agents of any type and at any scale in developing an ABM allows the model to simulate diverse phenomena normally studied by different disciplines. Finally, and most importantly, an ABM facilitates the participation of stakeholders in iterative rounds of modeling, in order to verify (ground truth) the results of the model and ensure its relevance to the real world problem situation.

In this project, an agent based model, KohTaoSim, was used to link a simplified coral reef eco-system to the social dynamics of dive tourism. KohTaoSim is able to capture the basic behavior of natural (coral reefs) and social (tourists, dive school and other institutions) system components, and interactions among them, as well as feedback dynamics between ecological and social-economic dimensions of the SES. The effects of these dynamics on coral reef health and tourism development under different environmental and management scenarios were simulated, tested and analyzed.

During the research period, KohTaoSim’s adjustable user interface, incorporating simulated real-life phenomena and local scientific knowledge, was found to be accessible to resource users. It was easy for them to get involved and contribute their opinions and knowledge (which were the principal data source used for model development). At the same time, the illustrated real-time and holistic presentation of resource users’ own living environment inspired them to reflect on their own situations, roles and behaviors. This “deeper and clearer” view of the living social-ecological environment facilitated the formulation and assessment of different management proposals by resource users (who were also the principal source for the management scenarios analyzed in this study).

In summary, this study was successful in using ABM as a tool for analysis of social-ecological dynamics and also to test the effects of different management approaches. It is one of the first studies of its kind applied to a coastal-marine environment. Furthermore, the model development process incorporating iterative participatory methods (interviews, focus groups and role playing games), transdisciplinary knowledge transformation (definition of model rules and algorithms), a range of parameterization procedures (indirect and direct) and the use of different validation methods (classic and ground truthing), may serve as a guide for future studies. Finally, the evaluation of management strategies provides useful inputs for decision-making aimed at enhancing the sustainability of coral-based dive tourism on Koh Tao.

4.4 Further potential developments for the KohTaoSim

4.4.1 Ecological aspects

The ecology of coral reefs is extremely simplified in KohTaoSim, since the principal aim was explore the interaction between ecological and social dimensions of the SES. The following ecological aspects could be incorporated into future versions of KohTaoSim in accordance with management and/or research objectives:

- Ecological or biological processes such as coral phase shifts, coral evolution and adaptation, fish–coral interactions, loss of biodiversity, fish and/or coral larvae migration, etc.
- A more detailed mapping of coastal pollution levels taking account of the locations of pollution sources. (Currently it is assumed that pollution is released all along the coastline).
- More detailed simulation on effects of global stressors such as sea level change and ocean acidification.
- More ecological data or investigation on parameterizing the direct damage of divers on coral reefs, as the availed data is so far limited and scarce.
- Consideration of the specific costs and potential benefits provided by different kinds of artificial reef, as well as the risks and trade-offs involved.

4.4.2 Social economic aspects

Due to time and resource constraints, some relevant socio-economics elements of the SES are not incorporated in the current version KohTaoSim. Future versions could take account of the following:

- The behavior of tourists in specific situations, for example in response to price rises to fund conservation measures or when unethical practices are observed at dive sites.
- Detailed characteristics of dive schools, such as size, accommodation type, etc.
- The economic costs of alternative waste water treatments (waste water plant or eco toilet/shower) and reforestation programs.
- The side-effects and longer-term effects of the environmental education program.

- The dynamics of other businesses (restaurants, retail stores etc.) that participate in the dive-based tourism industry.

4.5 Outlook

The model is intended as an open-access resource that is available to assist in local management decision-making processes. However the model does not encompass all aspects of the situation (and would not do so even if the aspects listed above were incorporated into future versions). Other pertinent issues, including acceptance of management suggestions at local level would need further research. Some studies argue that international programs (e.g. UNEP's sustainable tourism management agenda) and conceptual frameworks (integrated coastal management) cannot be directly transferred and implemented at the local level, because of location-specific differences in ecological, social-economic and managerial settings (Cicinsain and Belfiore 2005, Wongthong and Harvey 2014). However, considering the costs of developing a location-specific management plan, exemplified by this study, there is clearly scope for the development of a more generalized ABM (with flexible options for creating new parameters, defining algorithms, and setting baseline values; and facilities for automatic integration of some geographical information) as a more generally applicable, location-adaptable management tool.

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APPENDIX 1: Semi structured interviews

1.1 Coral- ecologists (3 respondents)

Basic information

Name: ……………………………………………

Institute: …………………………………………

Research interests: ……………………………..

Ecological information

Have you observed the coral health change?

Have you data to evident such change?

What can be the cause of such change?

Dive schools or snorkel trip company owner/managers (4 respondents)

Basic information

Name: ……………………………………………………..

Owner/manager of which dive school:……………………..

How many dive masters and dive instructors are working in your dive school?

How many SCUBA divers can be trained or accommodated at the same time?

What kind of courses are in offer?

How many SCUBA divers per dive group/ dive master for those courses?

How many dive group this dive school operate per day for each course?

What factors determine which dive spot to visit?

What is advantage of this dive school compare to others?

Questions toward dive schools

Activeness in NGO

How many NGOs for marine conservation is this dive school aware of? (If NGO is mentioned)

Whether a member of any NGO?

Why this dive school joins this NGO?

What you need to do to be a member of this NGO?

Environmental awareness

Is this dive school environmental-friendly? (If environmental friendly is mentioned)

What practices are there for environmental conservation?

What do these practices cost? (Time; petro; labour; facility)

To what extent will these environmental promotion or practices help to attract divers?

Are you satisfied with environment around Koh Tao? (If nice beach is mentioned)

If not, what is the reason?

Coral reef information

Do you believe that coral reef on Koh Tao island is degraded?

What can be the possible reason for this degradation? (Dive tourism; illegal fishing; snorkelling groups; full moon party rush; no waste treatment)

Does this degradation influence or will influence your business?

Economical information

Are you satisfied with tax you to pay to government?

What is the annual profit for your dive school?

How many SCUBA divers your dive school serve annually?

Social capacity of tourism (by using acceptable change level)

For this dive school's development, does this dive school expect more or less tourists on Koh Tao?

Questions towards snorkel trip company

Is snorkelling group a big threat for coral reef health?

How many snorkelling groups visit Koh Tao per day or per month?

How many people per group?

Where do they normally do snorkelling?

Are you satisfied with tax you pay to government?

What is the annual profit for your company?

How many snorkelers your dive school serve annually?

1.2 NGO leader/coordinators (3 respondents)

Basic information

Name: ………………………………..

Established since: ……………………

What is the administrative structure of this NGO?

How many members are in this NGO?

Who are they? (Name list?)

What is the mission of this NGO?

Coral reef information

Do you believe that coral reef on Koh Tao island is degraded?

What can be the possible reason for this degradation?

Operational and financial information

How to join this NGO?

What activities does this NGO regularly organize?

What successful effort has been done for this mission?

If there are efforts, how are they operated?

Where are the financial resources for these activities?

If there is no much effort, what is the limit?

Is there also support from tourists?

Eco-label information

Does this NGO offer eco-label to dive school?

What does dive school do to gain this label?

1.3 SCUBA divers (10 respondents)

Basic information

How long have you stayed here?

What is your nationality?

Which marine activity you are you participating in?

Which dive school did you choose?

Which diving courses did you take?

Preference information

Why did you choose Koh Tao as dive destiny?

Why did you choose this dive school?

Four pictures of different coral reef dive spot health level (very good, good, poor and very poor) will be shown to sampled tourists.

- ✧ Question 1, which picture is more likely to where you have dived around Koh Tao?
- ✧ Question 2, if the coral reef dive spot health gets worse, till which level will you still come back to Koh Tao and dive, if Koh Tao is still as cheap to get dive certificate as now?

NGO awareness

How many NGOs for conservation are you aware of? (If NGO is mentioned)

How did you get to know about these NGOs?

Did you do anything to support any NGO?

Environmental awareness

Is your dive school environmental-friendly? (If environmental friendly is mentioned)

What practices are there for environmental conservation?

Do you cooperate with these practices?

Satisfaction

Are you satisfied with your vacation on Koh Tao in general and recommend to other people?

If yes, what is the reason?

If not, what is the reason?

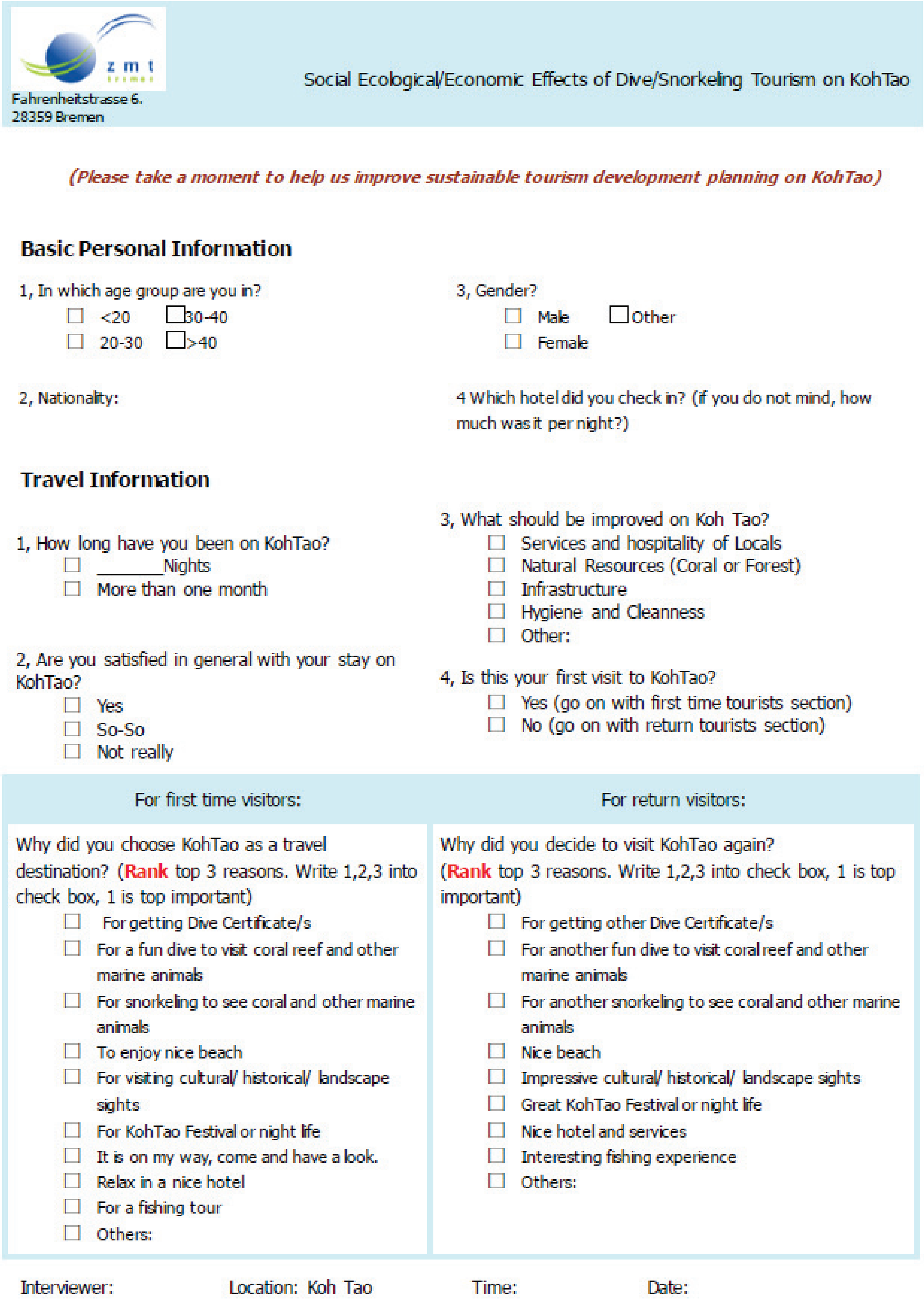
Coral reef information

Are you satisfied with coral reef condition here around Koh Tao?

If no, what can be the possible reason for bad coral reef condition?

Does coral reef condition influence or will influence your satisfaction of staying?

APPENDIX 2: Structured tourist questionnaire



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Social Ecological/Economic Effects of Dive/Snorkeling Tourism on KohTao

(Please take a moment to help us improve sustainable tourism development planning on KohTao)

Basic Personal Information

1, In which age group are you in?
- ☐ <20 ☐ 30-40
- ☐ 20-30 ☐ >40

2, Nationality:

3, Gender?
- ☐ Male ☐ Other
- ☐ Female

4 Which hotel did you check in? (if you do not mind, how much was it per night?)

Travel Information

1, How long have you been on KohTao?
- ☐ _______Nights
- ☐ More than one month

2, Are you satisfied in general with your stay on KohTao?
- ☐ Yes
- ☐ So-So
- ☐ Not really

3, What should be improved on Koh Tao?
- ☐ Services and hospitality of Locals
- ☐ Natural Resources (Coral or Forest)
- ☐ Infrastructure
- ☐ Hygiene and Cleanness
- ☐ Other:

4, Is this your first visit to KohTao?
- ☐ Yes (go on with first time tourists section)
- ☐ No (go on with return tourists section)

For first time visitors:	For return visitors:
Why did you choose KohTao as a travel destination? (**Rank** top 3 reasons. Write 1,2,3 into check box, 1 is top important)	Why did you decide to visit KohTao again? (**Rank** top 3 reasons. Write 1,2,3 into check box, 1 is top important)
☐ For getting Dive Certificate/s	☐ For getting other Dive Certificate/s
☐ For a fun dive to visit coral reef and other marine animals	☐ For another fun dive to visit coral reef and other marine animals
☐ For snorkeling to see coral and other marine animals	☐ For another snorkeling to see coral and other marine animals
☐ To enjoy nice beach	☐ Nice beach
☐ For visiting cultural/ historical/ landscape sights	☐ Impressive cultural/ historical/ landscape sights
☐ For KohTao Festival or night life	☐ Great KohTao Festival or night life
☐ It is on my way, come and have a look.	☐ Nice hotel and services
☐ Relax in a nice hotel	☐ Interesting fishing experience
☐ For a fishing tour	☐ Others:
☐ Others:	

Interviewer: Location: Koh Tao Time: Date:

Dive Information (if you have dived on KohTao)

1, With which dive school did you do fun dive or dive course? Which course?

2, Why did you choose this dive school?

- ☐ Affordable Price
- ☐ They offer marine conservation dive courses
- ☐ Recommendation from Marine Conservation Organization
- ☐ Recommendation from friends, Internet, books, locals on ferry or on the way to KohTao
- ☐ Nice accommodation
- ☐ Good services and instructors
- ☐ Nice location, next to beach or pier
- ☐ Others:

Conservation Information

1, Are you aware of any environment conservation organization?

- ☐ Yes, which one? __________
- ☐ No

2, Have you ever supported this environment conservation organization in any mean?

- ☐ Yes
- ☐

3, Are you aware of any conservation organization or activity on KohTao?

- ☐ Yes
- ☐ No

4, Were you involved in any conservation activity on Koh Tao (any kind of support)?

- ☐ Yes, which? _________
- ☐ No

Coral Health Information

A

B

C

1, Among the above pictures, which one is more similar to KohTao coral condition according to your experience?

- ☐ A
- ☐ B
- ☐ C

3, If KohTao coral health will stay in current condition, How likely would you come back here?

- ☐ Definitely
- ☐ Maybe
- ☐ No-Way!

2. Are you satisfied with the coral health condition in general around KohTao?

- ☐ No
- ☐ So-So
- ☐ Yes

4, Paying more money for your next dive or snorkel trip, can bring you to a healthier coral reef region, how much more per dive/snorkel would you be willing to pay?

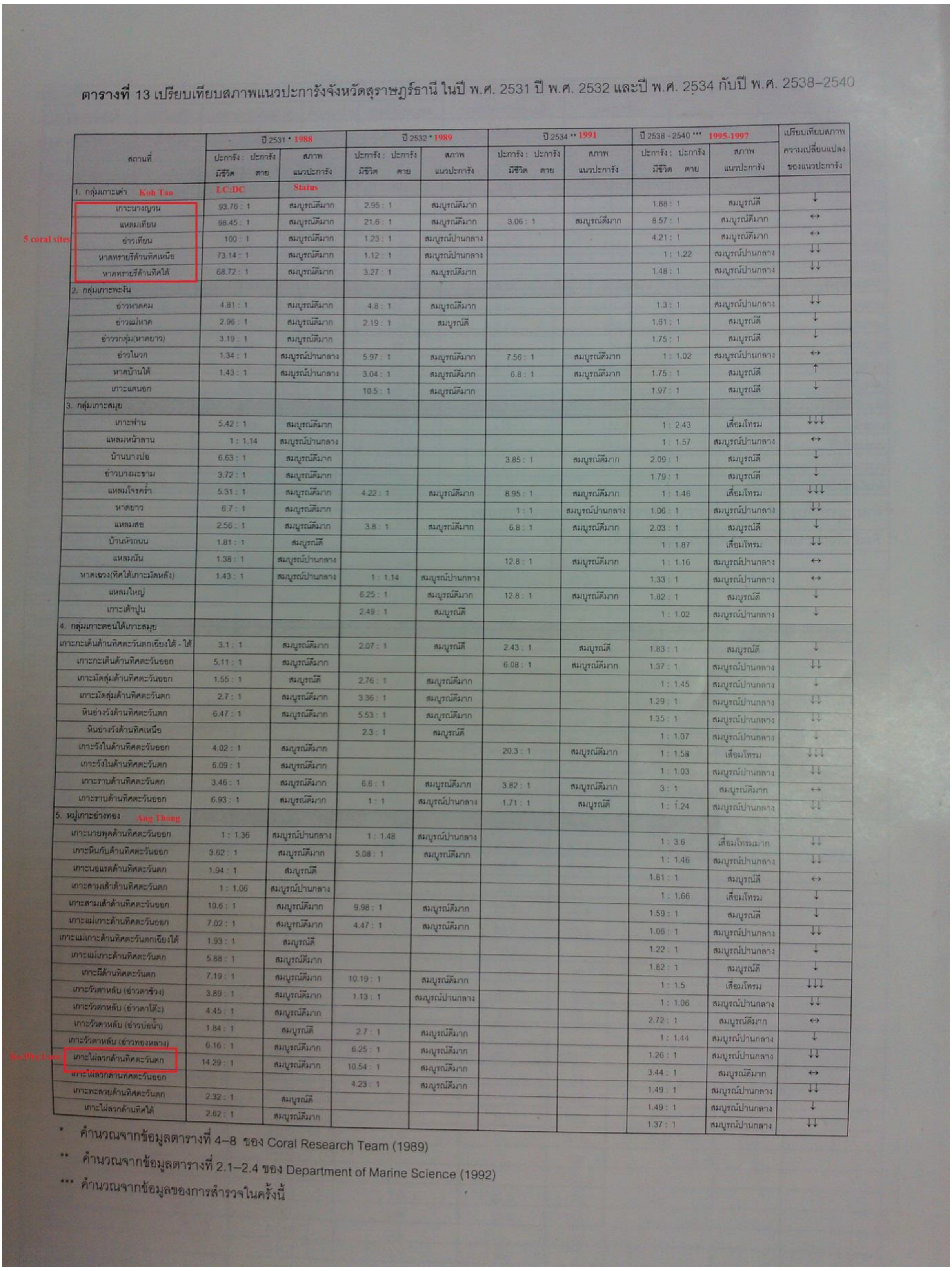
- ☐ 0 Baht
- ☐ _____ Baht

Thank you for your participation!

Interviewer:
Location: Koh Tao
Time:
Date:

APPENDIX 3: Secondary ecological data

3.1 Governmental documentation of historical coral health data from year 1988 to 1997. Information includes live coral (LC): dead coral (DC) cover rater for Koh Tao and AMNP. Manta tow technique was applied for this data base.



ตารางที่ 13 เปรียบเทียบสภาพแนวปะการังจังหวัดสุราษฎร์ธานี ในปี พ.ศ. 2531 ปี พ.ศ. 2532 และปี พ.ศ. 2534 กับปี พ.ศ. 2538–2540

สถานที่	ปี 2531 * 1988		ปี 2532 * 1989		ปี 2534 ** 1991		ปี 2538 - 2540 *** 1995-1997		เปรียบเทียบสภาพความเปลี่ยนแปลงของแนวปะการัง
	ปะการัง : ปะการัง มีชีวิต ตาย	สภาพแนวปะการัง	ปะการัง : ปะการัง มีชีวิต ตาย	สภาพแนวปะการัง	ปะการัง : ปะการัง มีชีวิต ตาย	สภาพแนวปะการัง	ปะการัง : ปะการัง มีชีวิต ตาย	สภาพแนวปะการัง	
1. กลุ่มเกาะเต่า Koh Tao	LC:DC	Status							
เกาะนางญวน	93.76 : 1	สมบูรณ์ดีมาก	2.95 : 1	สมบูรณ์ดีมาก			1.88 : 1	สมบูรณ์ดี	↓
แหลมเทียน	98.45 : 1	สมบูรณ์ดีมาก	21.6 : 1	สมบูรณ์ดีมาก	3.06 : 1	สมบูรณ์ดีมาก	8.57 : 1	สมบูรณ์ดีมาก	↔
อ่าวเทียน	100 : 1	สมบูรณ์ดีมาก	1.23 : 1	สมบูรณ์ปานกลาง			4.21 : 1	สมบูรณ์ดีมาก	↔
หาดทรายรีด้านทิศเหนือ	73.14 : 1	สมบูรณ์ดีมาก	1.12 : 1	สมบูรณ์ปานกลาง			1 : 1.22	สมบูรณ์ปานกลาง	↓↓
หาดทรายรีด้านทิศใต้	68.72 : 1	สมบูรณ์ดีมาก	3.27 : 1	สมบูรณ์ดีมาก			1.48 : 1	สมบูรณ์ปานกลาง	↓↓
2. กลุ่มเกาะพะงัน									
อ่าวหาดคม	4.81 : 1	สมบูรณ์ดีมาก	4.8 : 1	สมบูรณ์ดีมาก			1.3 : 1	สมบูรณ์ปานกลาง	↓↓
อ่าวแม่หาด	2.96 : 1	สมบูรณ์ดีมาก	2.19 : 1	สมบูรณ์ดี			1.61 : 1	สมบูรณ์ดี	↓
อ่าววกตุ่ม(หาดยาว)	3.19 : 1	สมบูรณ์ดีมาก					1.75 : 1	สมบูรณ์ดี	↓
อ่าวในวก	1.34 : 1	สมบูรณ์ปานกลาง	5.97 : 1	สมบูรณ์ดีมาก	7.56 : 1	สมบูรณ์ดีมาก	1 : 1.02	สมบูรณ์ปานกลาง	↔
หาดบ้านใต้	1.43 : 1	สมบูรณ์ปานกลาง	3.04 : 1	สมบูรณ์ดีมาก	6.8 : 1	สมบูรณ์ดีมาก	1.75 : 1	สมบูรณ์ดี	↑
เกาะแตนอก			10.5 : 1	สมบูรณ์ดีมาก			1.97 : 1	สมบูรณ์ดี	↓
3. กลุ่มเกาะสมุย									
เกาะฟาน	5.42 : 1	สมบูรณ์ดีมาก					1 : 2.43	เสื่อมโทรม	↓↓↓
แหลมหน้าลาน	1 : 1.14	สมบูรณ์ปานกลาง					1 : 1.57	สมบูรณ์ปานกลาง	↔
บ้านบางปอ	6.63 : 1	สมบูรณ์ดีมาก			3.85 : 1	สมบูรณ์ดีมาก	2.09 : 1	สมบูรณ์ดี	↓
อ่าวบางมะขาม	3.72 : 1	สมบูรณ์ดีมาก					1.79 : 1	สมบูรณ์ดี	↓
แหลมโจรคร่ำ	5.31 : 1	สมบูรณ์ดีมาก	4.22 : 1	สมบูรณ์ดีมาก	8.95 : 1	สมบูรณ์ดีมาก	1 : 1.46	เสื่อมโทรม	↓↓↓
หาดยาว	6.7 : 1	สมบูรณ์ดีมาก			1 : 1	สมบูรณ์ปานกลาง	1.06 : 1	สมบูรณ์ปานกลาง	↓↓
แหลมสอ	2.56 : 1	สมบูรณ์ดีมาก	3.8 : 1	สมบูรณ์ดีมาก	6.8 : 1	สมบูรณ์ดีมาก	2.03 : 1	สมบูรณ์ดี	↓
บ้านหัวถนน	1.81 : 1	สมบูรณ์ดี					1 : 1.87	เสื่อมโทรม	↓↓
แหลมนัน	1.38 : 1	สมบูรณ์ปานกลาง			12.8 : 1	สมบูรณ์ดีมาก	1 : 1.16	สมบูรณ์ปานกลาง	↔
หาดเฉวง(ทิศใต้เกาะมัดหลัง)	1.43 : 1	สมบูรณ์ปานกลาง	1 : 1.14	สมบูรณ์ปานกลาง			1.33 : 1	สมบูรณ์ปานกลาง	↔
แหลมใหญ่			6.25 : 1	สมบูรณ์ดีมาก	12.8 : 1	สมบูรณ์ดีมาก	1.82 : 1	สมบูรณ์ดี	↓
เกาะเต่าปูน			2.49 : 1	สมบูรณ์ดี			1 : 1.02	สมบูรณ์ปานกลาง	↓
4. กลุ่มเกาะตอนใต้เกาะสมุย									
เกาะกะเต็นด้านทิศตะวันตกเฉียงใต้ - ใต้	3.1 : 1	สมบูรณ์ดีมาก	2.07 : 1	สมบูรณ์ดี	2.43 : 1	สมบูรณ์ดี	1.83 : 1	สมบูรณ์ดี	↓
เกาะกะเต็นด้านทิศตะวันออก	5.11 : 1	สมบูรณ์ดีมาก			6.08 : 1	สมบูรณ์ดีมาก	1.37 : 1	สมบูรณ์ปานกลาง	↓↓
เกาะมัดสุ่มด้านทิศตะวันออก	1.55 : 1	สมบูรณ์ดี	2.76 : 1	สมบูรณ์ดีมาก			1 : 1.45	สมบูรณ์ปานกลาง	↓
เกาะมัดสุ่มด้านทิศตะวันตก	2.7 : 1	สมบูรณ์ดีมาก	3.36 : 1	สมบูรณ์ดีมาก			1.29 : 1	สมบูรณ์ปานกลาง	↓↓
หินอ่างวังด้านทิศตะวันตก	6.47 : 1	สมบูรณ์ดีมาก	5.53 : 1	สมบูรณ์ดีมาก			1.35 : 1	สมบูรณ์ปานกลาง	↓↓
หินอ่างวังด้านทิศเหนือ			2.3 : 1	สมบูรณ์ดี			1 : 1.07	สมบูรณ์ปานกลาง	↓
เกาะวังในด้านทิศตะวันออก	4.02 : 1	สมบูรณ์ดีมาก			20.3 : 1	สมบูรณ์ดีมาก	1 : 1.58	เสื่อมโทรม	↓↓↓
เกาะวังในด้านทิศตะวันตก	6.09 : 1	สมบูรณ์ดีมาก					1 : 1.03	สมบูรณ์ปานกลาง	↓↓
เกาะราบด้านทิศตะวันตก	3.46 : 1	สมบูรณ์ดีมาก	6.6 : 1	สมบูรณ์ดีมาก	3.82 : 1	สมบูรณ์ดีมาก	3 : 1	สมบูรณ์ดีมาก	↔
เกาะราบด้านทิศตะวันออก	6.93 : 1	สมบูรณ์ดีมาก	1 : 1	สมบูรณ์ปานกลาง	1.71 : 1	สมบูรณ์ดี	1 : 1.24	สมบูรณ์ปานกลาง	↓↓
5. หมู่เกาะอ่างทอง Ang Thong									
เกาะนายพุดด้านทิศตะวันออก	1 : 1.36	สมบูรณ์ปานกลาง	1 : 1.48	สมบูรณ์ปานกลาง			1 : 3.6	เสื่อมโทรมมาก	↓↓
เกาะหินกับด้านทิศตะวันออก	3.62 : 1	สมบูรณ์ดีมาก	5.08 : 1	สมบูรณ์ดีมาก			1 : 1.46	สมบูรณ์ปานกลาง	↓↓
เกาะนอแรดด้านทิศตะวันตก	1.94 : 1	สมบูรณ์ดี					1.81 : 1	สมบูรณ์ดี	↔
เกาะสามเส้าด้านทิศตะวันตก	1 : 1.06	สมบูรณ์ปานกลาง					1 : 1.66	เสื่อมโทรม	↓
เกาะสามเส้าด้านทิศตะวันออก	10.6 : 1	สมบูรณ์ดีมาก	9.98 : 1	สมบูรณ์ดีมาก			1.59 : 1	สมบูรณ์ดี	↓
เกาะแม่เกาะด้านทิศตะวันออก	7.02 : 1	สมบูรณ์ดีมาก	4.47 : 1	สมบูรณ์ดีมาก			1.06 : 1	สมบูรณ์ปานกลาง	↓↓
เกาะแม่เกาะด้านทิศตะวันตกเฉียงใต้	1.93 : 1	สมบูรณ์ดี					1.22 : 1	สมบูรณ์ปานกลาง	↓
เกาะแม่เกาะด้านทิศตะวันตก	5.88 : 1	สมบูรณ์ดีมาก					1.82 : 1	สมบูรณ์ดี	↓
เกาะผีด้านทิศตะวันตก	7.19 : 1	สมบูรณ์ดีมาก	10.19 : 1	สมบูรณ์ดีมาก			1 : 1.5	เสื่อมโทรม	↓↓↓
เกาะวัวตาหลับ (อ่าวตาช้วง)	3.89 : 1	สมบูรณ์ดีมาก	1.13 : 1	สมบูรณ์ปานกลาง			1 : 1.06	สมบูรณ์ปานกลาง	↓↓
เกาะวัวตาหลับ (อ่าวตาโต๊ะ)	4.45 : 1	สมบูรณ์ดีมาก					2.72 : 1	สมบูรณ์ดีมาก	↔
เกาะวัวตาหลับ (อ่าวบ่อน้ำ)	1.84 : 1	สมบูรณ์ดี	2.7 : 1	สมบูรณ์ดีมาก			1 : 1.44	สมบูรณ์ปานกลาง	↓
เกาะวัวตาหลับ (อ่าวทองหลาง)	6.16 : 1	สมบูรณ์ดีมาก	6.25 : 1	สมบูรณ์ดีมาก			1.26 : 1	สมบูรณ์ปานกลาง	↓↓
เกาะไผ่ลวกด้านทิศตะวันตก	14.29 : 1	สมบูรณ์ดีมาก	10.54 : 1	สมบูรณ์ดีมาก			3.44 : 1	สมบูรณ์ดีมาก	↔
เกาะไผ่ลวกด้านทิศตะวันออก			4.23 : 1	สมบูรณ์ดีมาก			1.49 : 1	สมบูรณ์ปานกลาง	↓↓
เกาะพะลวยด้านทิศตะวันตก	2.32 : 1	สมบูรณ์ดี					1.49 : 1	สมบูรณ์ปานกลาง	↓
เกาะไผ่ลวกด้านทิศใต้	2.62 : 1	สมบูรณ์ดีมาก					1.37 : 1	สมบูรณ์ปานกลาง	↓↓

5 coral sites

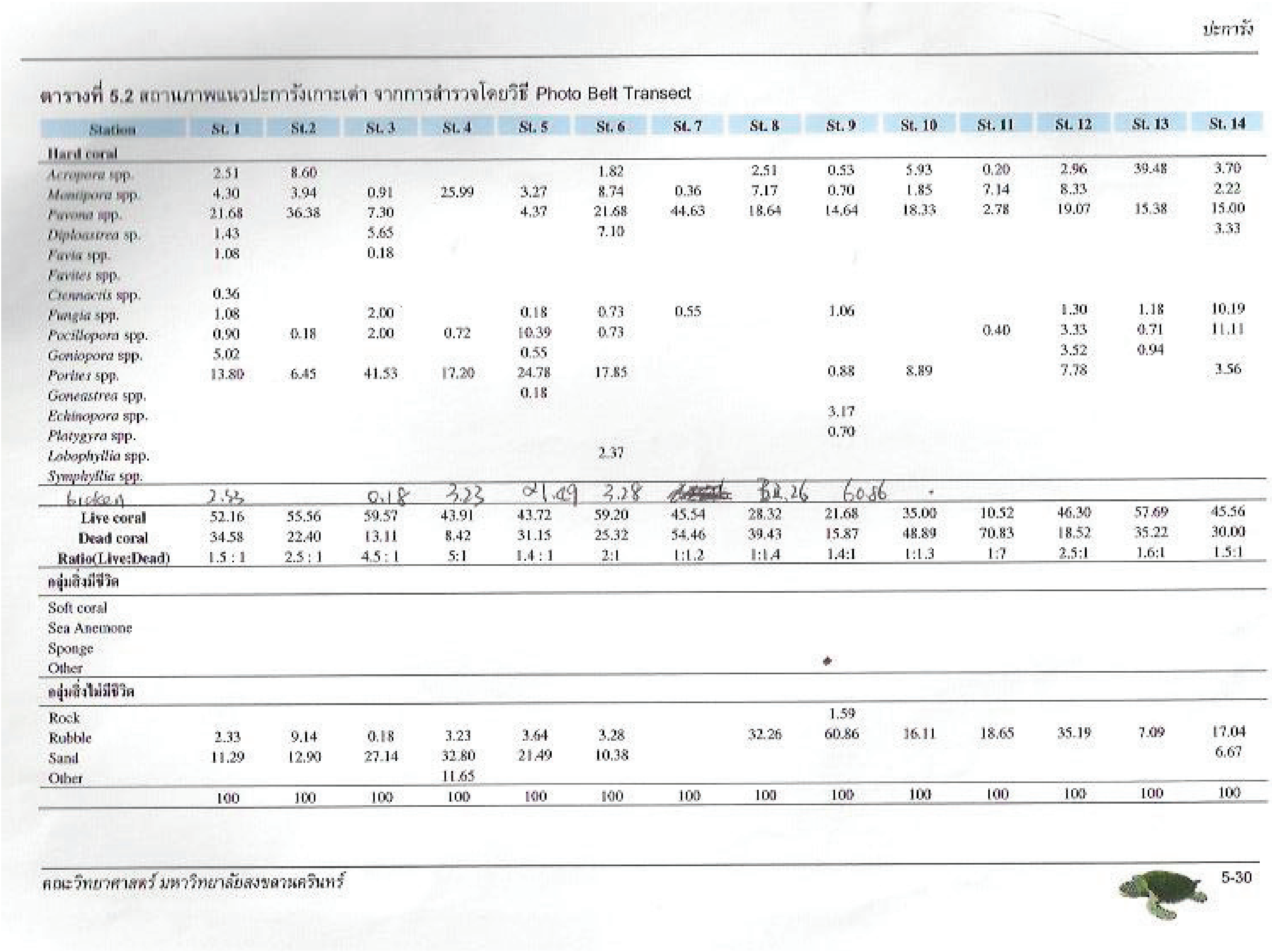
* คำนวณจากข้อมูลตารางที่ 4–8 ของ Coral Research Team (1989)

** คำนวณจากข้อมูลตารางที่ 2.1–2.4 ของ Department of Marine Science (1992)

*** คำนวณจากข้อมูลของการสำรวจในครั้งนี้

3.2 Governmental report (unpublished) of national coral survey in 2006: section Koh Tao. Manta tow technique was applied for this data base.

รูปที่ 5.1 สถานีเก็บตัวอย่างปะการังบริเวณเกาะเต่า จังหวัดสุราษฎร์ธานี จำนวน 56 สถานี



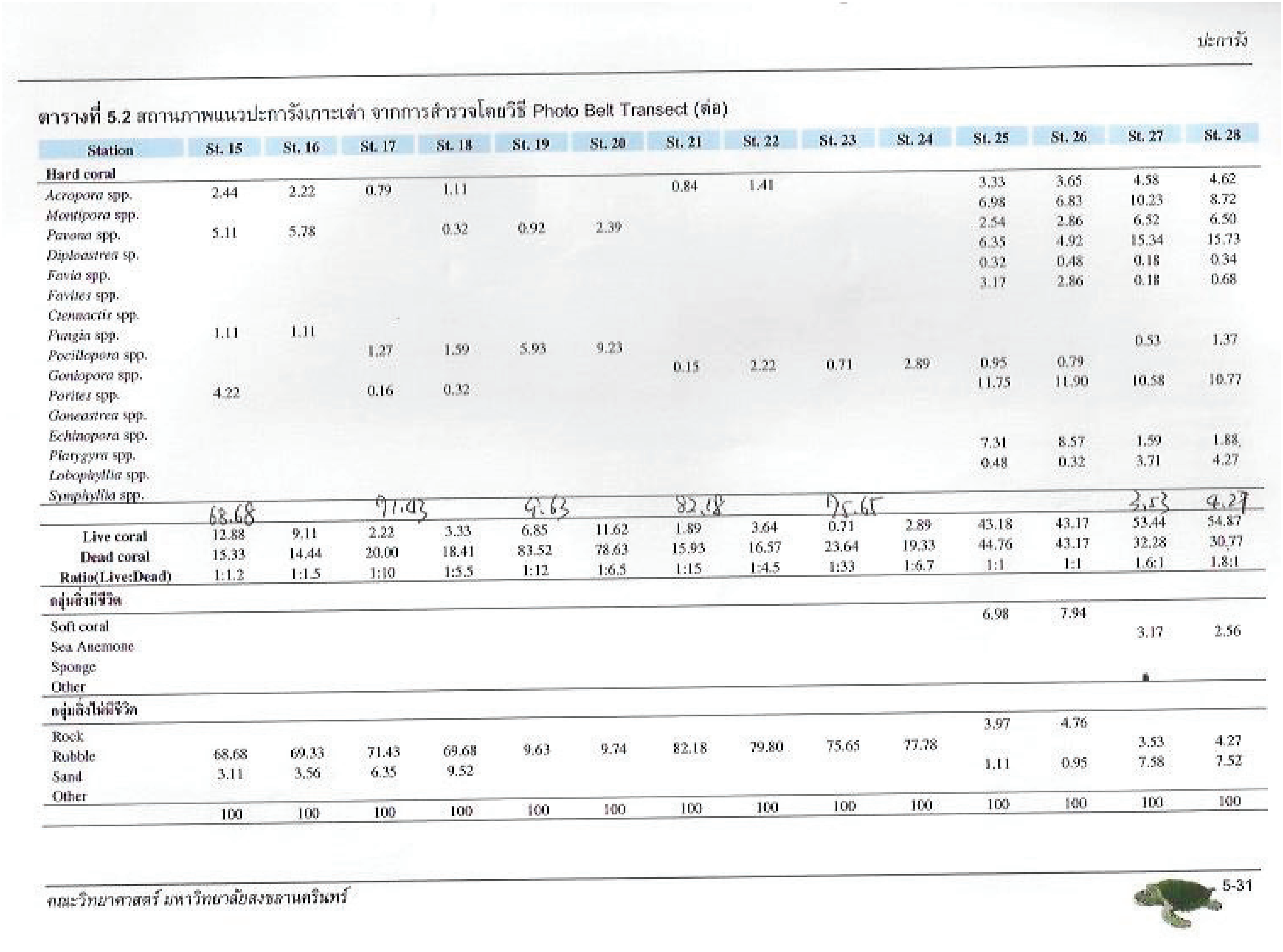
ปะการัง

ตารางที่ 5.2 สถานภาพแนวปะการังเกาะเต่า จากการสำรวจโดยวิธี Photo Belt Transect

Station	St. 1	St.2	St. 3	St. 4	St. 5	St. 6	St. 7	St. 8	St. 9	St. 10	St. 11	St. 12	St. 13	St. 14
Hard coral														
Acropora spp.	2.51	8.60				1.82		2.51	0.53	5.93	0.20	2.96	39.48	3.70
Montipora spp.	4.30	3.94	0.91	25.99	3.27	8.74	0.36	7.17	0.70	1.85	7.14	8.33		2.22
Pavona spp.	21.68	36.38	7.30		4.37	21.68	44.63	18.64	14.64	18.33	2.78	19.07	15.38	15.00
Diploastrea sp.	1.43		5.65			7.10								3.33
Favia spp.	1.08		0.18											
Favites spp.														
Ctenactis spp.	0.36													
Fungia spp.	1.08		2.00		0.18	0.73	0.55		1.06			1.30	1.18	10.19
Pocillopora spp.	0.90	0.18	2.00	0.72	10.39	0.73					0.40	3.33	0.71	11.11
Goniopora spp.	5.02				0.55							3.52	0.94	
Porites spp.	13.80	6.45	41.53	17.20	24.78	17.85			0.88	8.89		7.78		3.56
Goneastrea spp.					0.18									
Echinopora spp.									3.17					
Platygyra spp.									0.70					
Lobophyllia spp.						2.37								
Symphyllia spp.														
broken	2.33		0.18	3.23	21.49	3.28		32.26	60.86					
Live coral	52.16	55.56	59.57	43.91	43.72	59.20	45.54	28.32	21.68	35.00	10.52	46.30	57.69	45.56
Dead coral	34.58	22.40	13.11	8.42	31.15	25.32	54.46	39.43	15.87	48.89	70.83	18.52	35.22	30.00
Ratio(Live:Dead)	1.5 : 1	2.5 : 1	4.5 : 1	5:1	1.4 : 1	2:1	1:1.2	1:1.4	1.4:1	1:1.3	1:7	2.5:1	1.6:1	1.5:1
กลุ่มสิ่งมีชีวิต														
Soft coral														
Sea Anemone														
Sponge														
Other														
กลุ่มสิ่งไม่มีชีวิต														
Rock									1.59					
Rubble	2.33	9.14	0.18	3.23	3.64	3.28		32.26	60.86	16.11	18.65	35.19	7.09	17.04
Sand	11.29	12.90	27.14	32.80	21.49	10.38								6.67
Other				11.65										
	100	100	100	100	100	100	100	100	100	100	100	100	100	100

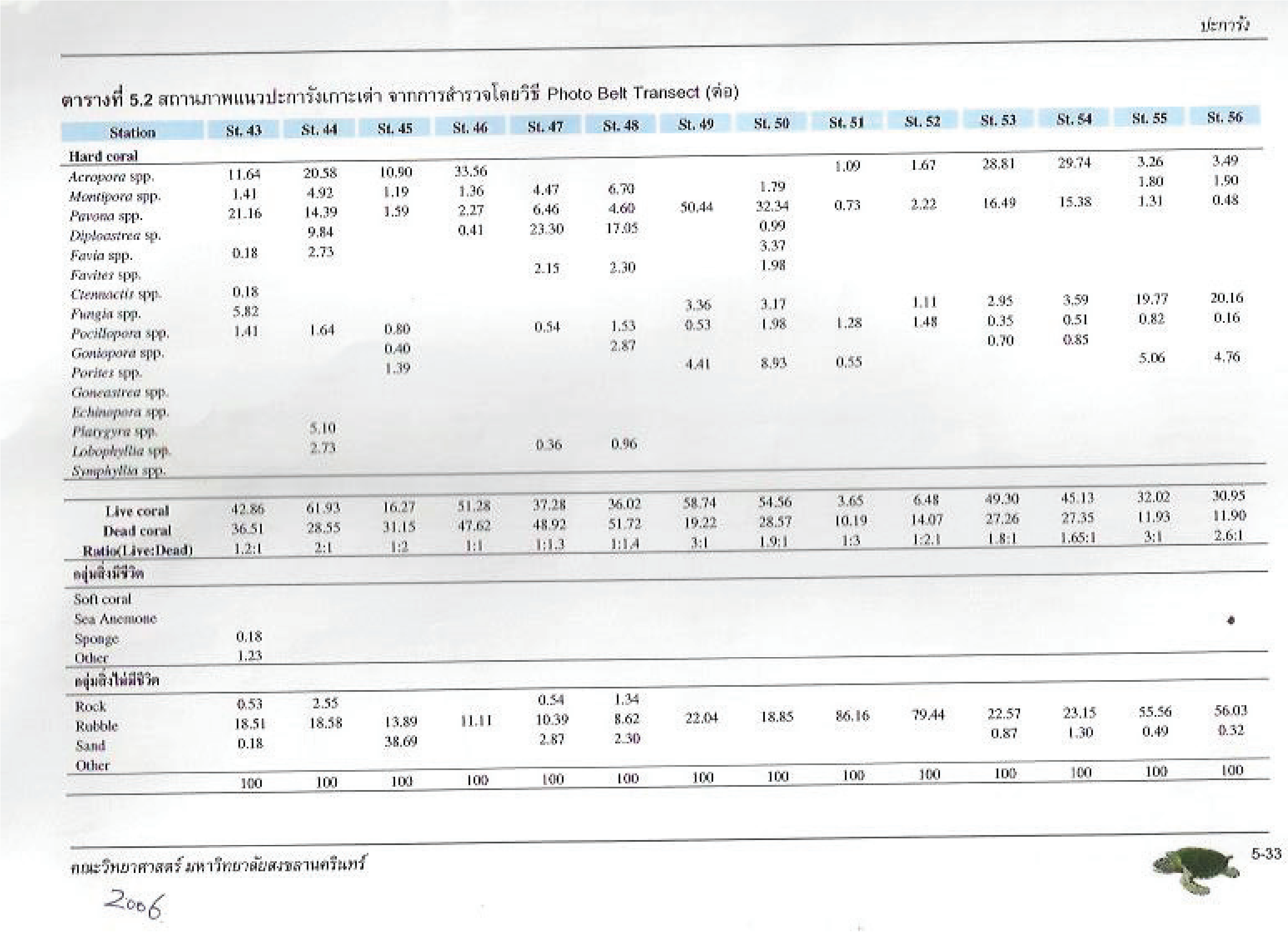
คณะวิทยาศาสตร์ มหาวิทยาลัยสงขลานครินทร์

5-30



ตารางที่ 5.2 สถานภาพแนวปะการังเกาะเต่า จากการสำรวจโดยวิธี Photo Belt Transect (ต่อ)

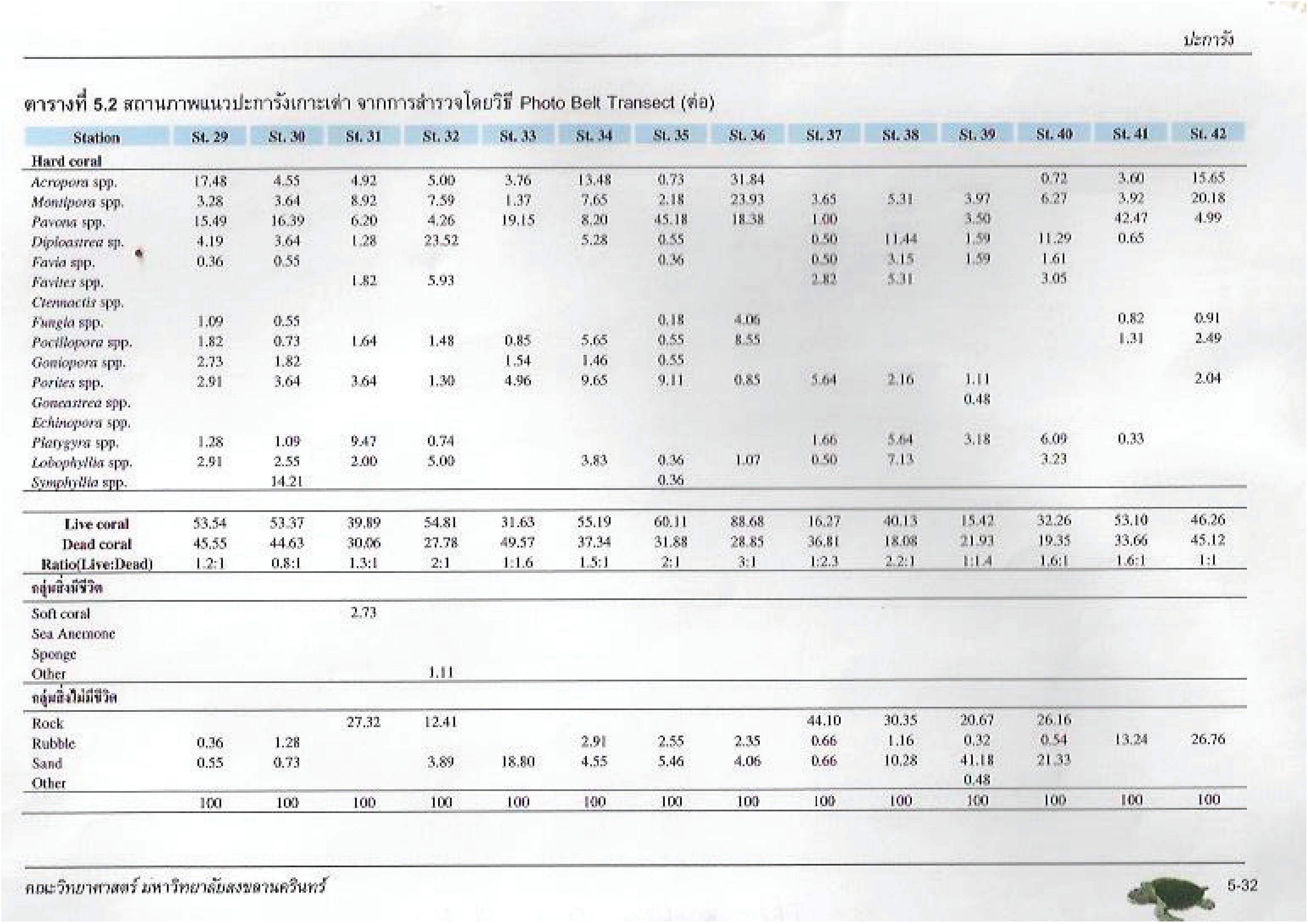
Station	St. 15	St. 16	St. 17	St. 18	St. 19	St. 20	St. 21	St. 22	St. 23	St. 24	St. 25	St. 26	St. 27	St. 28
Hard coral														
Acropora spp.	2.44	2.22	0.79	1.11			0.84	1.41			3.33	3.65	4.58	4.62
Montipora spp.											6.98	6.83	10.23	8.72
Pavona spp.	5.11	5.78		0.32	0.92	2.39					2.54	2.86	6.52	6.50
Diploastrea sp.											6.35	4.92	15.34	15.73
Favia spp.											0.32	0.48	0.18	0.34
Favites spp.											3.17	2.86	0.18	0.68
Ctenactis spp.														
Fungia spp.	1.11	1.11												
Pocillopora spp.			1.27	1.59	5.93	9.23							0.53	1.37
Goniopora spp.							0.15	2.22	0.71	2.89	0.95	0.79		
Porites spp.	4.22		0.16	0.32							11.75	11.90	10.58	10.77
Goneastrea spp.														
Echinopora spp.														
Platygyra spp.											7.31	8.57	1.59	1.88
Lobophyllia spp.											0.48	0.32	3.71	4.27
Symphyllia spp.														
	68.68		71.43		9.63		82.18		75.65				3.53	4.27
Live coral	12.88	9.11	2.22	3.33	6.85	11.62	1.89	3.64	0.71	2.89	43.18	43.17	53.44	54.87
Dead coral	15.33	14.44	20.00	18.41	83.52	78.63	15.93	16.57	23.64	19.33	44.76	43.17	32.28	30.77
Ratio(Live:Dead)	1:1.2	1:1.5	1:10	1:5.5	1:12	1:6.5	1:15	1:4.5	1:33	1:6.7	1:1	1:1	1.6:1	1.8:1
กลุ่มสิ่งมีชีวิต														
Soft coral											6.98	7.94		
Sea Anemone													3.17	2.56
Sponge														
Other														
กลุ่มสิ่งไม่มีชีวิต														
Rock											3.97	4.76		
Rubble	68.68	69.33	71.43	69.68	9.63	9.74	82.18	79.80	75.65	77.78			3.53	4.27
Sand	3.11	3.56	6.35	9.52							1.11	0.95	7.58	7.52
Other														
	100	100	100	100	100	100	100	100	100	100	100	100	100	100



ตารางที่ 5.2 สถานภาพแนวปะการังเกาะเต่า จากการสำรวจโดยวิธี Photo Belt Transect (ต่อ)

Station	St. 43	St. 44	St. 45	St. 46	St. 47	St. 48	St. 49	St. 50	St. 51	St. 52	St. 53	St. 54	St. 55	St. 56
Hard coral														
Acropora spp.	11.64	20.58	10.90	33.56					1.09	1.67	28.81	29.74	3.26	3.49
Montipora spp.	1.41	4.92	1.19	1.36	4.47	6.70		1.79					1.80	1.90
Pavona spp.	21.16	14.39	1.59	2.27	6.46	4.60	50.44	32.34	0.73	2.22	16.49	15.38	1.31	0.48
Diploastrea sp.		9.84		0.41	23.30	17.05		0.99						
Favia spp.	0.18	2.73						3.37						
Favites spp.					2.15	2.30		1.98						
Ctenactis spp.	0.18													
Fungia spp.	5.82						3.36	3.17		1.11	2.95	3.59	19.77	20.16
Pocillopora spp.	1.41	1.64	0.80		0.54	1.53	0.53	1.98	1.28	1.48	0.35	0.51	0.82	0.16
Goniopora spp.			0.40			2.87					0.70	0.85		
Porites spp.			1.39				4.41	8.93	0.55				5.06	4.76
Goneastrea spp.														
Echinopora spp.														
Platygyra spp.		5.10												
Lobophyllia spp.		2.73			0.36	0.96								
Symphyllia spp.														
Live coral	42.86	61.93	16.27	51.28	37.28	36.02	58.74	54.56	3.65	6.48	49.30	45.13	32.02	30.95
Dead coral	36.51	28.55	31.15	47.62	48.92	51.72	19.22	28.57	10.19	14.07	27.26	27.35	11.93	11.90
Ratio(Live:Dead)	1.2:1	2:1	1:2	1:1	1:1.3	1:1.4	3:1	1.9:1	1:3	1:2.1	1.8:1	1.65:1	3:1	2.6:1
กลุ่มสิ่งมีชีวิต														
Soft coral														
Sea Anemone														
Sponge	0.18													
Other	1.23													
กลุ่มสิ่งไม่มีชีวิต														
Rock	0.53	2.55			0.54	1.34								
Rubble	18.51	18.58	13.89	11.11	10.39	8.62	22.04	18.85	86.16	79.44	22.57	23.15	55.56	56.03
Sand	0.18		38.69		2.87	2.30					0.87	1.30	0.49	0.32
Other														
	100	100	100	100	100	100	100	100	100	100	100	100	100	100

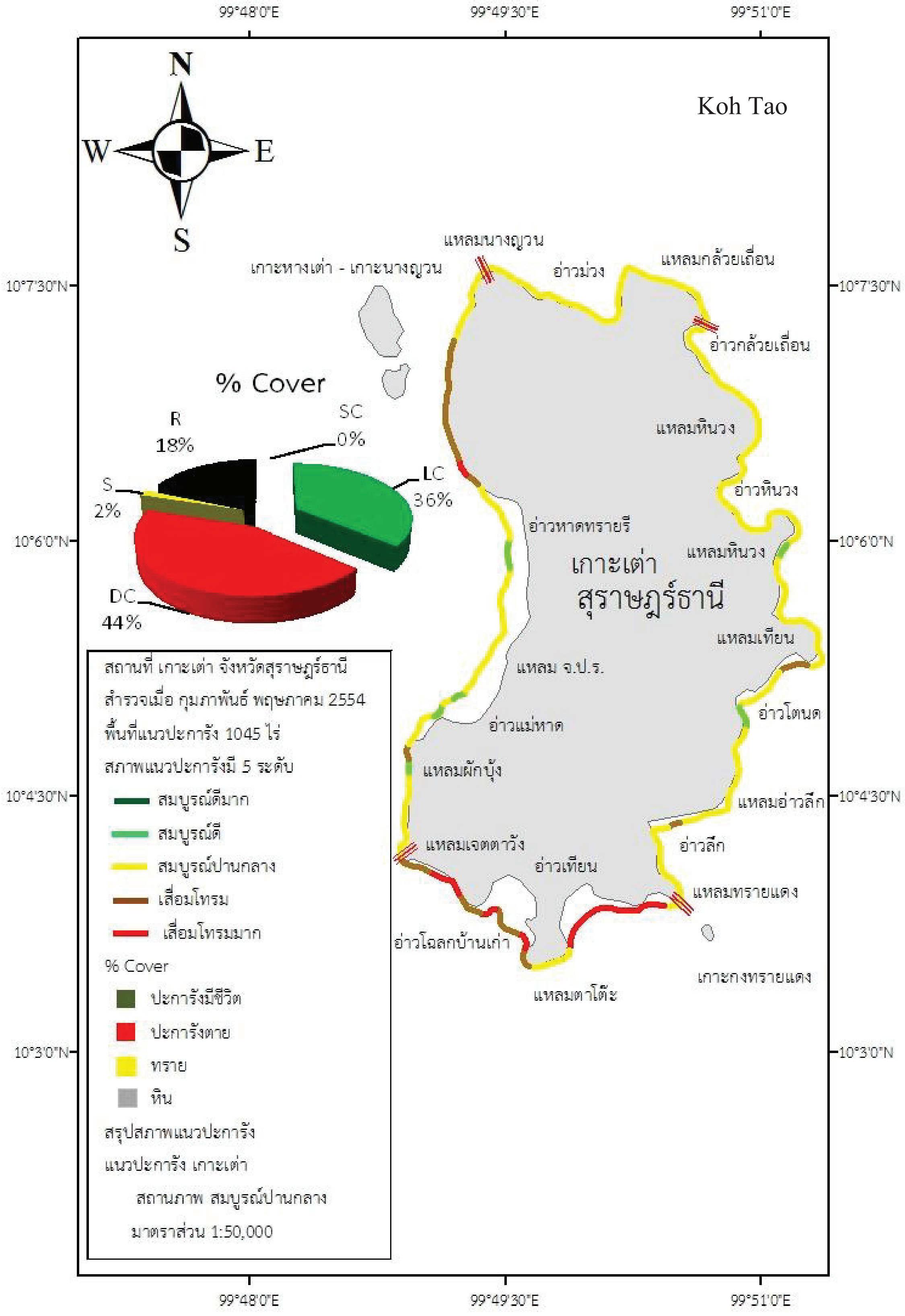
2006

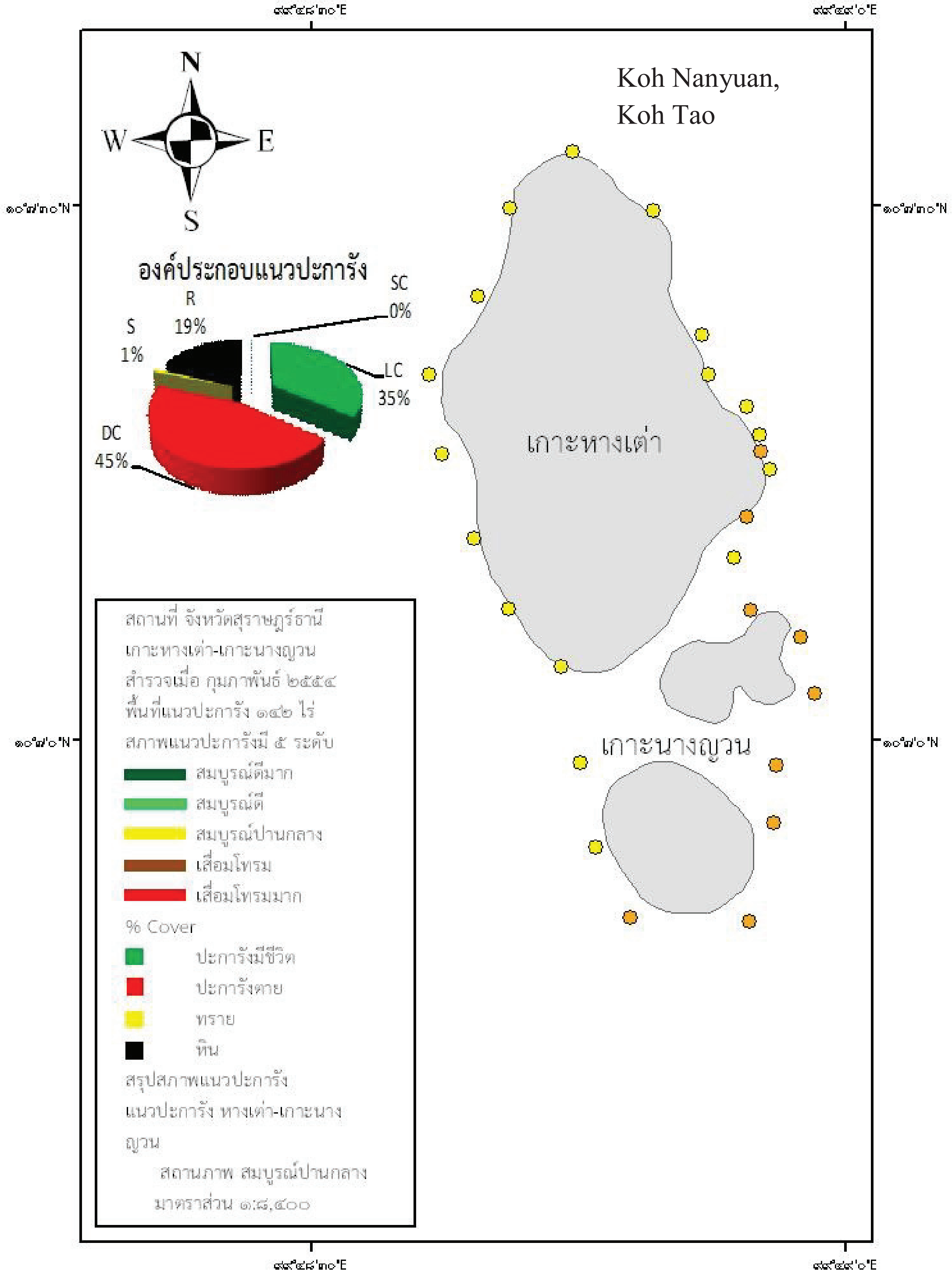


ตารางที่ 5.2 สถานภาพแนวปะการังเกาะเต่า จากการสำรวจโดยวิธี Photo Belt Transect (ต่อ)

Station	St. 29	St. 30	St. 31	St. 32	St. 33	St. 34	St. 35	St. 36	St. 37	St. 38	St. 39	St. 40	St. 41	St. 42
Hard coral														
Acropora spp.	17.48	4.55	4.92	5.00	3.76	13.48	0.73	31.84				0.72	3.60	15.65
Montipora spp.	3.28	3.64	8.92	7.59	1.37	7.65	2.18	23.93	3.65	5.31	3.97	6.27	3.92	20.18
Pavona spp.	15.49	16.39	6.20	4.26	19.15	8.20	45.18	18.38	1.00		3.50		42.47	4.99
Diploastrea sp.	4.19	3.64	1.28	23.52		5.28	0.55		0.50	11.44	1.59	11.29	0.65	
Favia spp.	0.36	0.55					0.36		0.50	3.15	1.59	1.61		
Favites spp.			1.82	5.93					2.82	5.31		3.05		
Ctennactis spp.														
Fungia spp.	1.09	0.55					0.18	4.06					0.82	0.91
Pocillopora spp.	1.82	0.73	1.64	1.48	0.85	5.65	0.55	8.55					1.31	2.49
Goniopora spp.	2.73	1.82			1.54	1.46	0.55							
Porites spp.	2.91	3.64	3.64	1.30	4.96	9.65	9.11	0.85	5.64	2.16	1.11			2.04
Goneastrea spp.											0.48			
Echinopora spp.														
Platygyra spp.	1.28	1.09	9.47	0.74					1.66	5.64	3.18	6.09	0.33	
Lobophyllia spp.	2.91	2.55	2.00	5.00		3.83	0.36	1.07	0.50	7.13		3.23		
Symphyllia spp.		14.21					0.36							
Live coral	53.54	53.37	39.89	54.81	31.63	55.19	60.11	88.68	16.27	40.13	15.42	32.26	53.10	46.26
Dead coral	45.55	44.63	30.06	27.78	49.57	37.34	31.88	28.85	36.81	18.08	21.93	19.35	33.66	45.12
Ratio(Live:Dead)	1.2:1	0.8:1	1.3:1	2:1	1:1.6	1.5:1	2:1	3:1	1:2.3	2.2:1	1:1.4	1.6:1	1.6:1	1:1
กลุ่มสิ่งมีชีวิต														
Soft coral			2.73											
Sea Anemone														
Sponge														
Other				1.11										
กลุ่มสิ่งไม่มีชีวิต														
Rock			27.32	12.41					44.10	30.35	20.67	26.16		
Rubble	0.36	1.28				2.91	2.55	2.35	0.66	1.16	0.32	0.54	13.24	26.76
Sand	0.55	0.73		3.89	18.80	4.55	5.46	4.06	0.66	10.28	41.18	21.33		
Other											0.48			
	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Appendix 3.3: Coral health survey result in 2011 by DMCR, Thailand (unpublished). Manta tow technique was applied for this data base.

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เกาะหางเต่า
เกาะนางญวน
สถานที่ จังหวัดสุราษฎร์ธานี
เกาะหางเต่า-เกาะนางญวน
สำรวจเมื่อ กุมภาพันธ์ ๒๕๕๔
พื้นที่แนวปะการัง ๑๔๒ ไร่
สภาพแนวปะการังมี ๕ ระดับ
สมบูรณ์ดีมาก
สมบูรณ์ดี
สมบูรณ์ปานกลาง
เสื่อมโทรม
เสื่อมโทรมมาก
% Cover
ปะการังมีชีวิต
ปะการังตาย
ทราย
หิน
สรุปสภาพแนวปะการัง
แนวปะการัง หางเต่า-เกาะนาง
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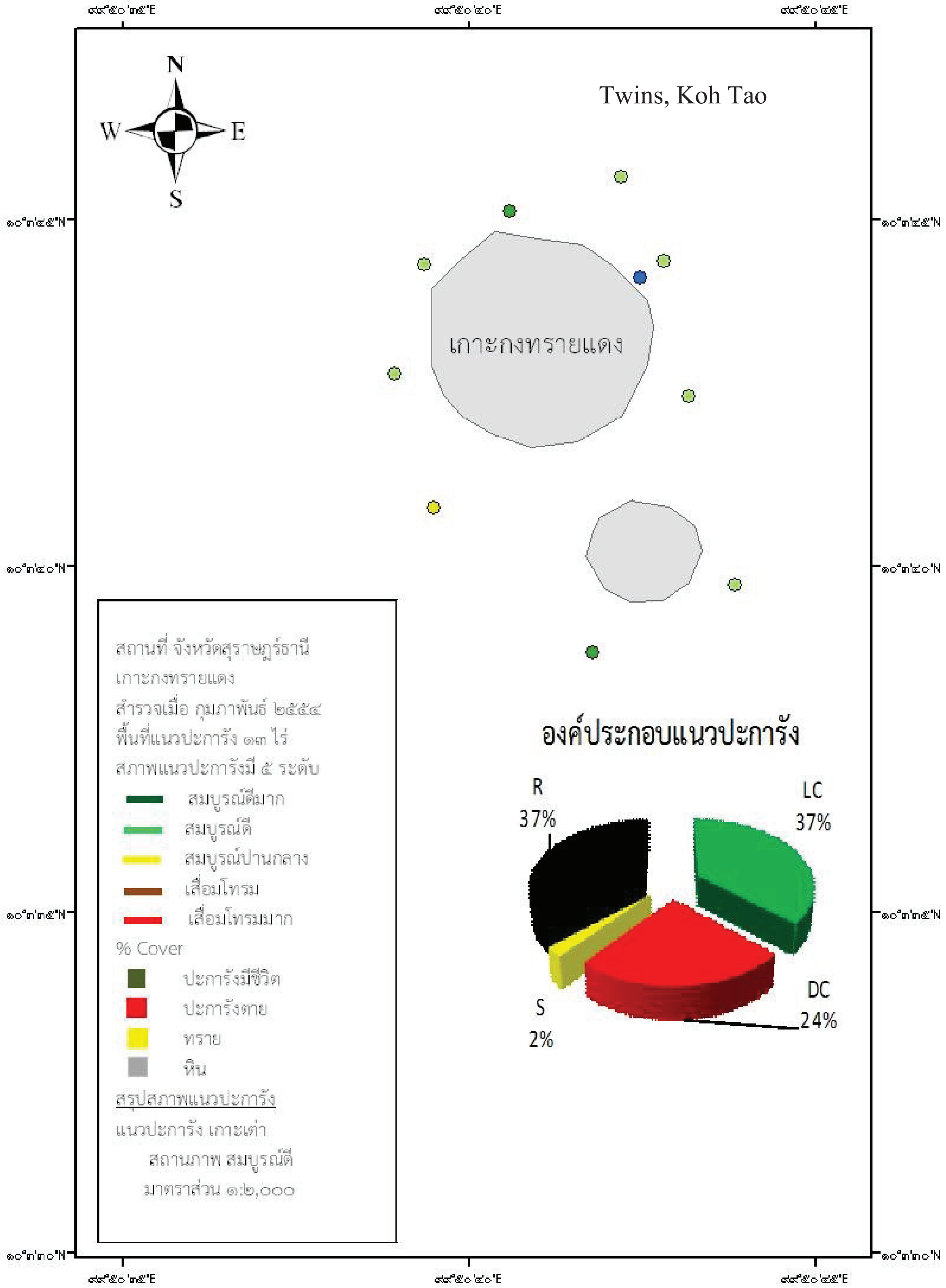
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Twins, Koh Tao
เกาะกงทรายแดง
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เกาะกงทรายแดง
สำรวจเมื่อ กุมภาพันธ์ ๒๕๕๔
พื้นที่แนวปะการัง ๑๓ ไร่
สภาพแนวปะการังมี ๕ ระดับ
สมบูรณ์ดีมาก
สมบูรณ์ดี
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ปะการังมีชีวิต
ปะการังตาย
ทราย
หิน
สรุปสภาพแนวปะการัง
แนวปะการัง เกาะเต่า
สถานภาพ สมบูรณ์ดี
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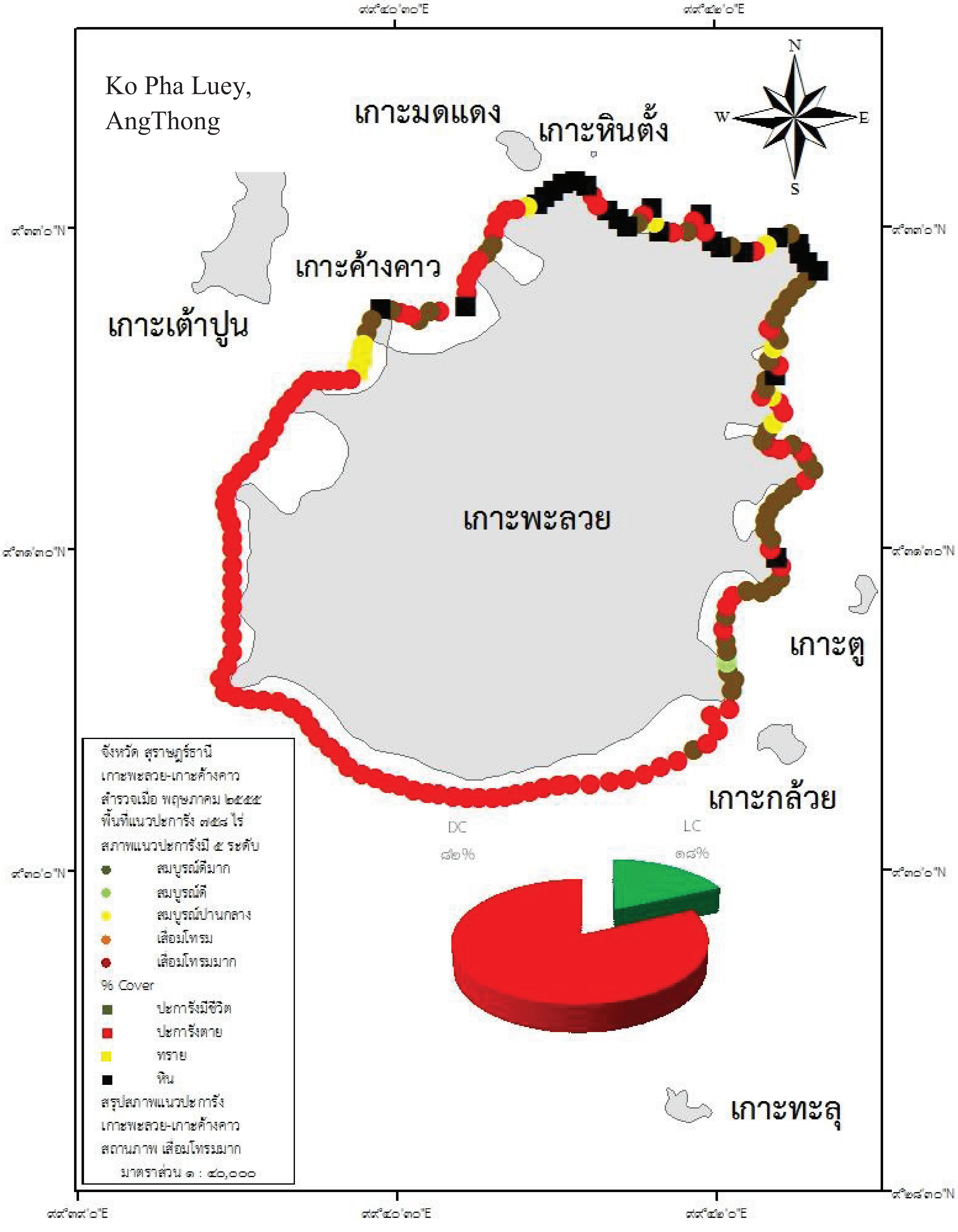
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AngThong
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เกาะตู
เกาะกล้วย
จังหวัด สุราษฎร์ธานี
เกาะพะลวย-เกาะค้างคาว
สำรวจเมื่อ พฤษภาคม ๒๕๕๕
พื้นที่แนวปะการัง ๗๕๘ ไร่
สภาพแนวปะการังมี ๕ ระดับ
● สมบูรณ์ดีมาก
● สมบูรณ์ดี
● สมบูรณ์ปานกลาง
● เสื่อมโทรม
● เสื่อมโทรมมาก
% Cover
■ ปะการังมีชีวิต
■ ปะการังตาย
■ ทราย
■ หิน
สรุปสภาพแนวปะการัง
เกาะพะลวย-เกาะค้างคาว
สถานภาพ เสื่อมโทรมมาก
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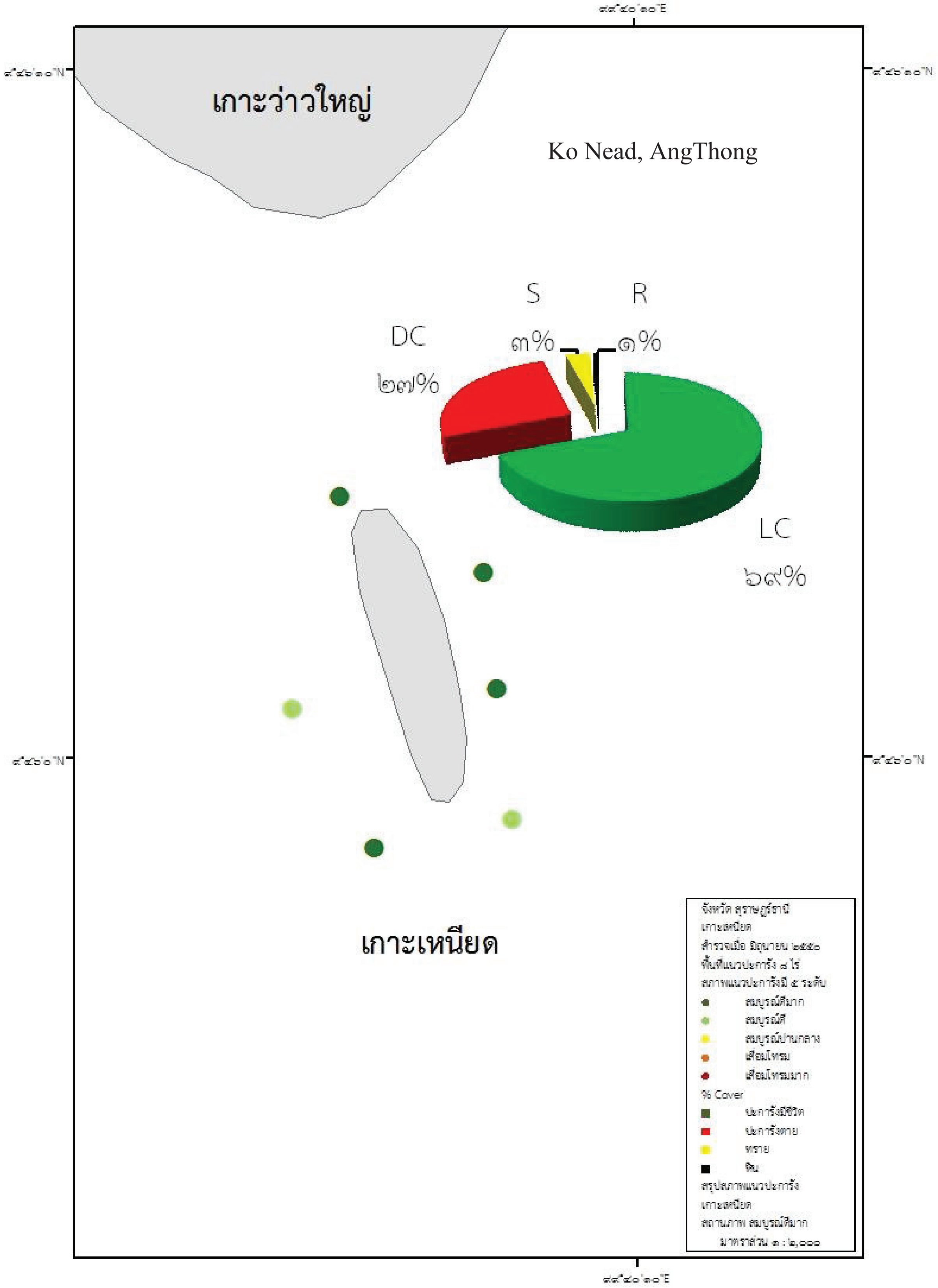
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เกาะว่าวใหญ่
Ko Nead, AngThong
S
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R
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DC
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LC
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๙°๔๖'๐"N
เกาะเหนียด
จังหวัด สุราษฎร์ธานี
เกาะเหนียด
สำรวจเมื่อ มิถุนายน ๒๕๕๐
พื้นที่แนวปะการัง ๘ ไร่
สภาพแนวปะการังมี ๕ ระดับ
● สมบูรณ์ดีมาก
● สมบูรณ์ดี
● สมบูรณ์ปานกลาง
● เสื่อมโทรม
● เสื่อมโทรมมาก
% Cover
🟩 ปะการังมีชีวิต
🟥 ปะการังตาย
🟨 ทราย
■ หิน
สรุปสภาพแนวปะการัง
เกาะเหนียด
สถานภาพ สมบูรณ์ดีมาก
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APPENDIX 4 Sensitivity Analysis results

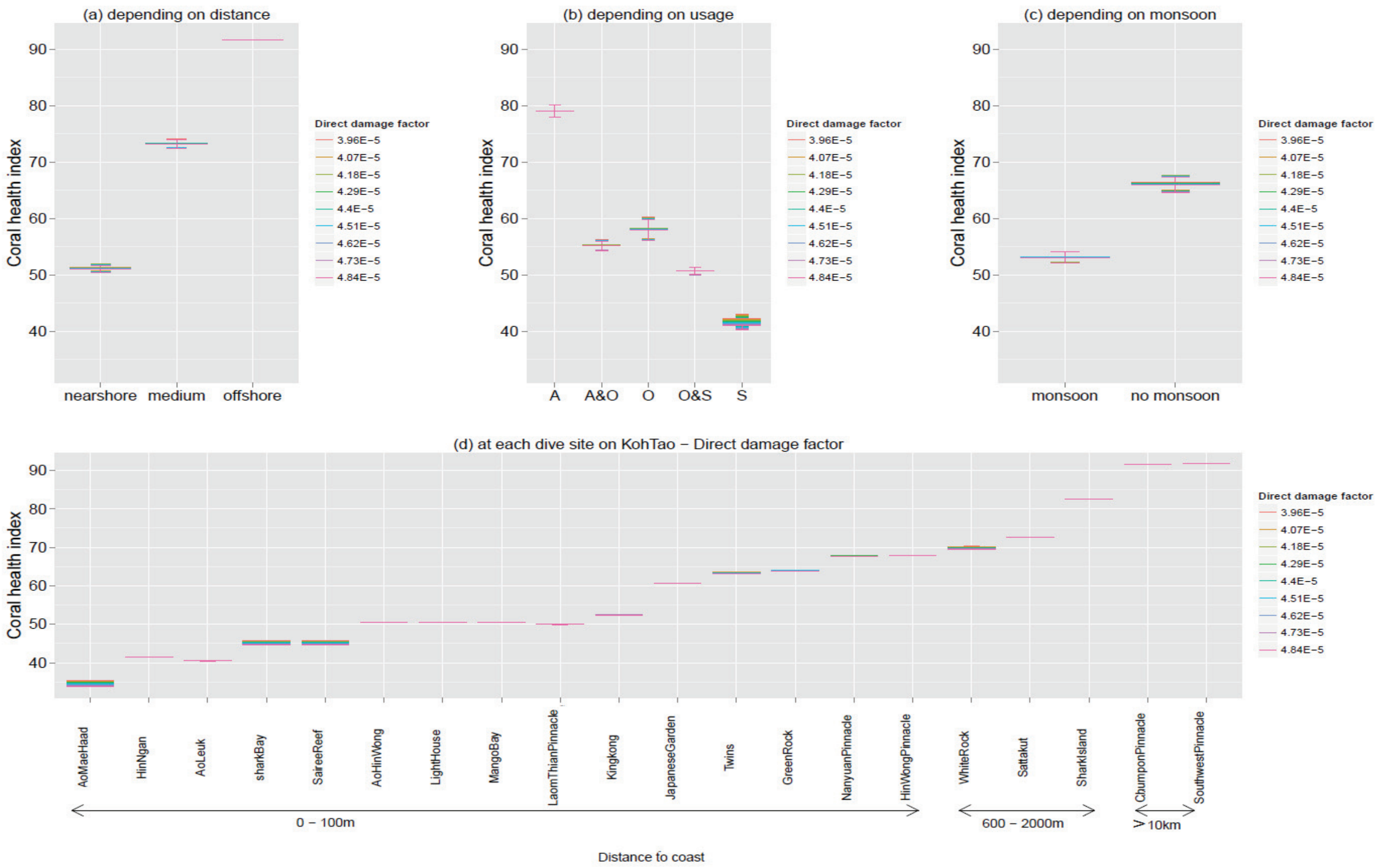


Figure A4.1: Coral health index respond from the direct damage factor varies by ± 10% with each step 2.5%. (a) Group the dive sites according to distance to coast as nearshore; medium; offshore; (b) Group the dive sites according to the dive type as A-advanced SCUBA dive site; A&O-advanced and open water SCUBA dive site; O-open water SCUBA dive site; O&S-oepn water SCUBA dive site and snorkeling site; S-snorkeling site; (c) Group the dive sites according to whether they are influenced in monsoon season. (d) all the dive site ranking according to their distance to coast.

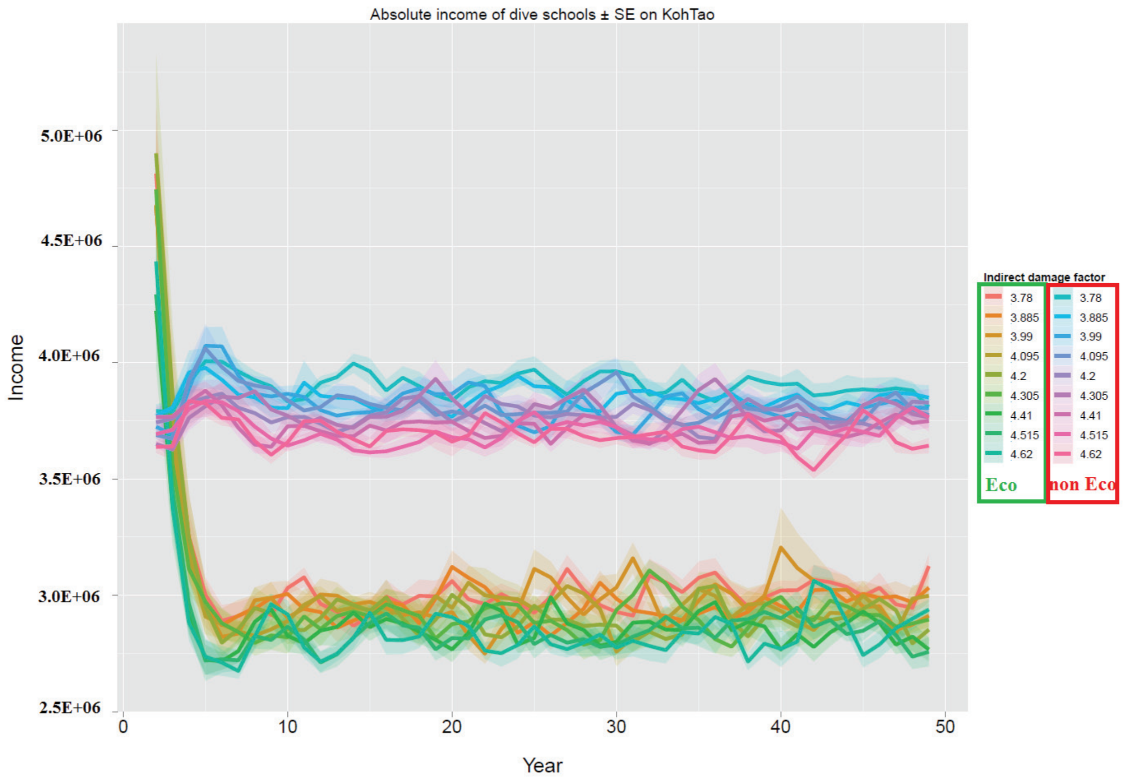


Figure A4.2: Change in mean total income of non-eco and eco-dive schools in response to change (±10% in steps of 2.5%) in the value of indirect damage factor (*Di*). The shaded areas represent the standard deviations of values from multiple simulation runs.

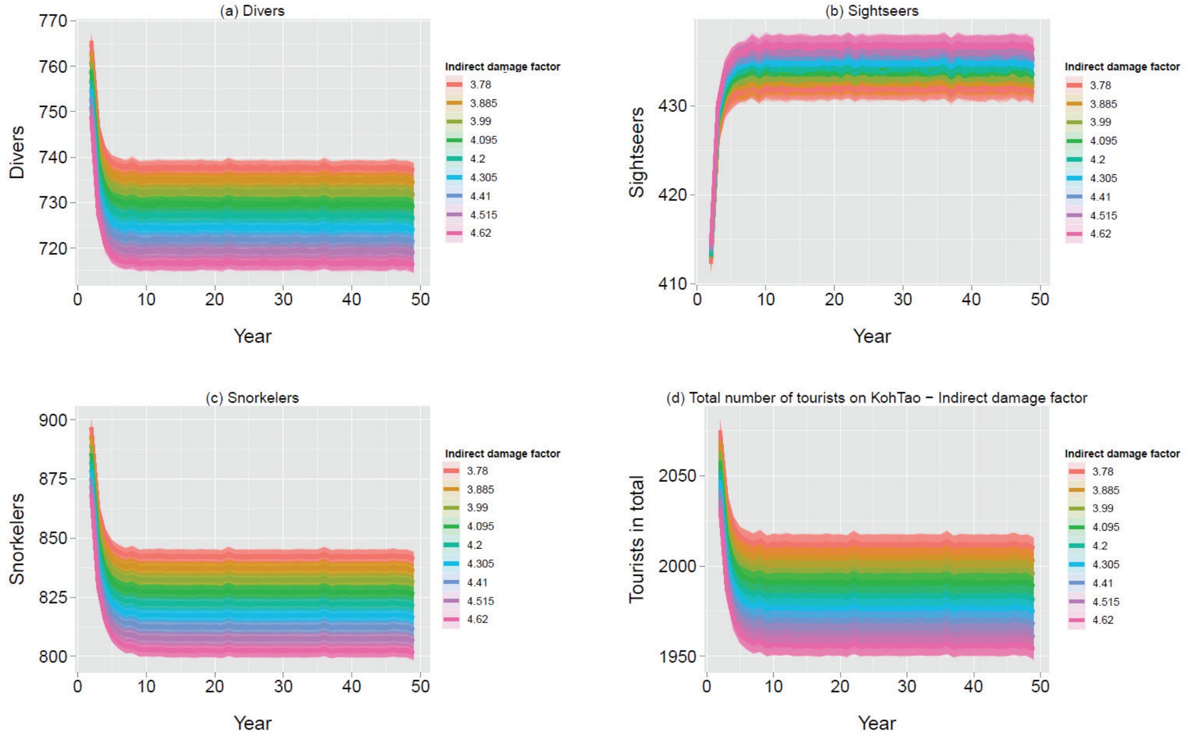


Figure A4.3: Change in tourist numbers in response to change (±10% in steps of 2.5%) in the value of indirect damage factor (*Di*): (a) SCUBA divers; (b) sightseers; (c) snorkelers; (d) all tourists.

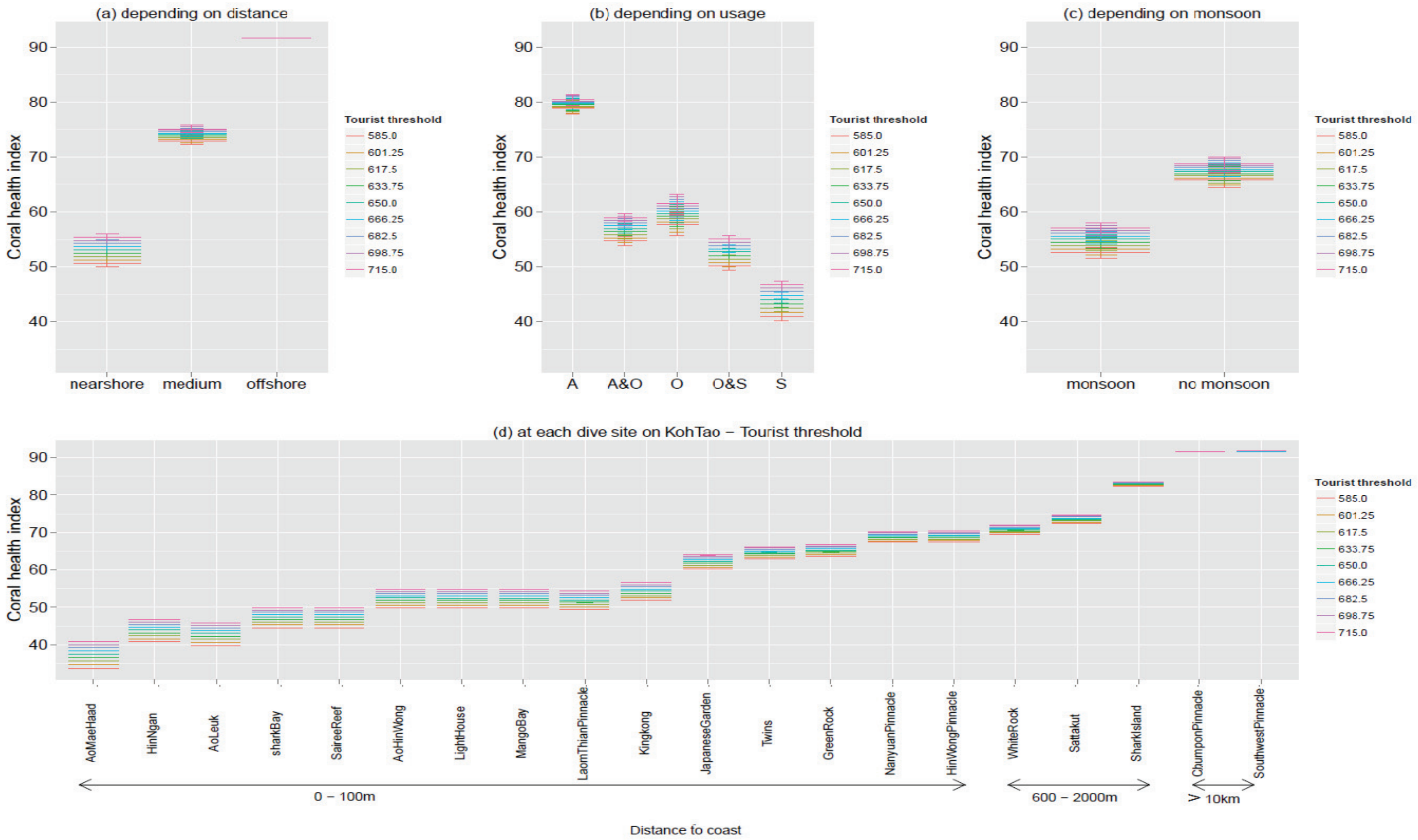


Figure A4.4: Changes in coral health index (Ht) values in response to changes (by up to ±10% in steps of 2.5%) in the value of the population threshold (Pthr): (a) dive sites grouped according to distance to coast as nearshore, medium and offshore; (b) dive sites grouped according to the dive type as advanced SCUBA dive site (A), advanced and open water SCUBA dive site (A&O), open water SCUBA dive site (O), open water SCUBA dive site and snorkelling site (O&S) and snorkelling site (S); (c) dive sites grouped according to whether they are influenced in monsoon season; (d) all dive sites ranked according to their distance from the coast.

Figure A4.5: Changes in mean total income of non-eco and eco-dive schools in response to change (±10% in steps of 2.5%) in the value of the population threshold (Pthr): The shaded areas represent the standard deviations of values from multiple simulation runs.

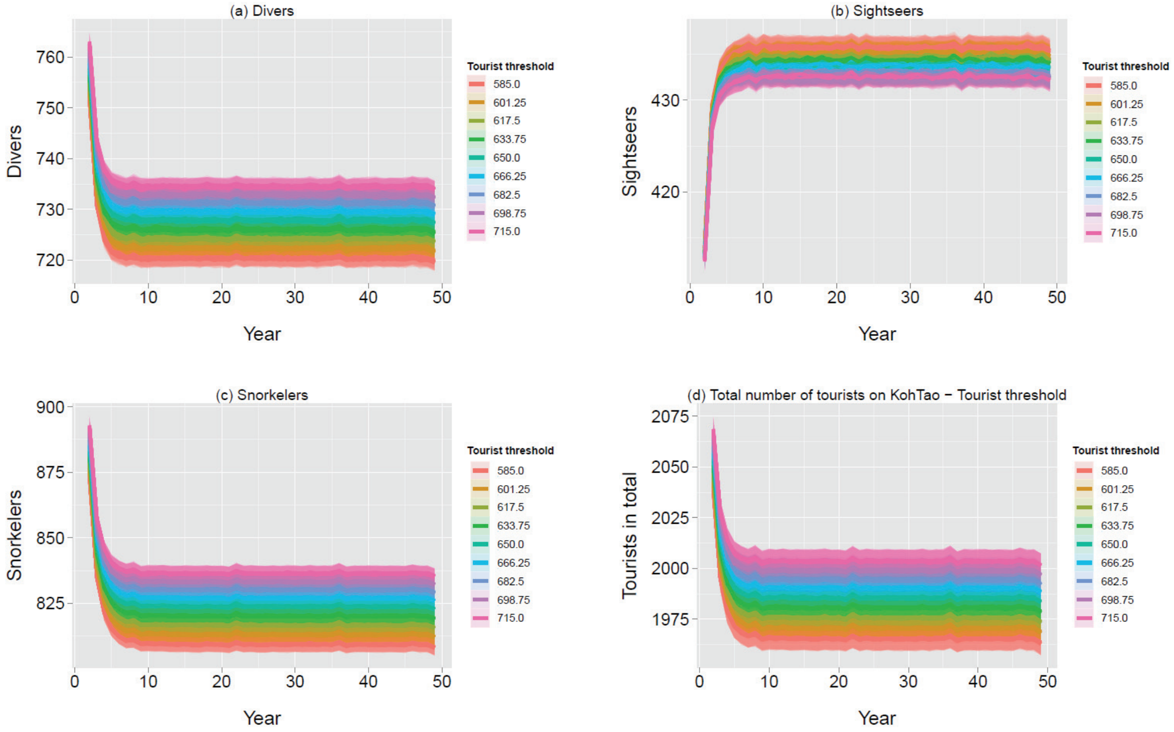
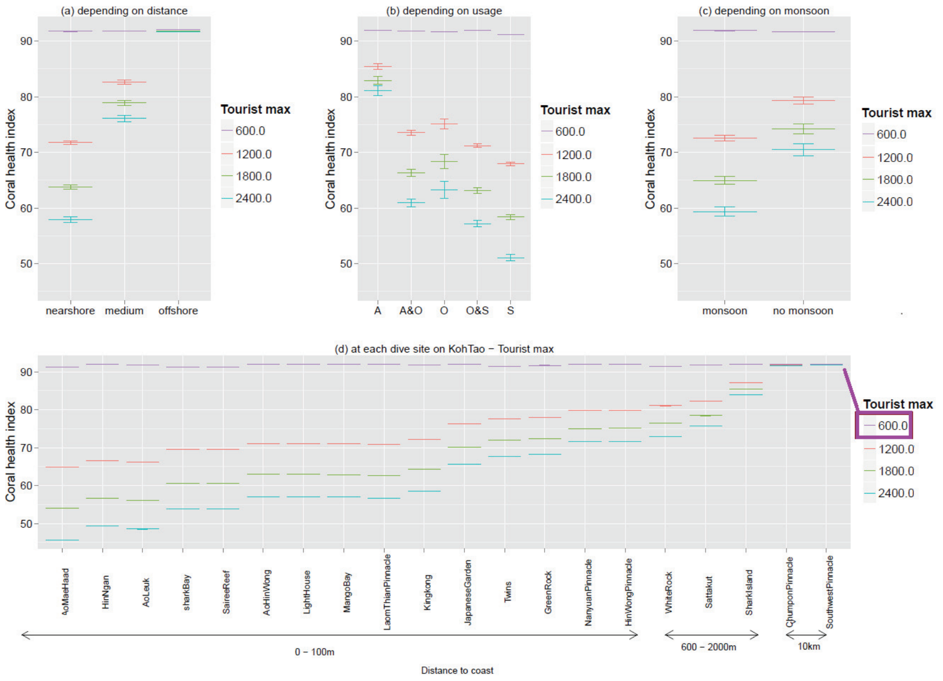


Figure A4.6: Changes in tourist numbers in response to change (±10% in steps of 2.5%) in the value of the population threshold (Pthr): (a) SCUBA divers; (b) sightseers; (c) snorkelers; (d) all tourists.

APPENDIX 5: Additional figures for result and discussion

Low visitor number scenario



High visitor number scenario

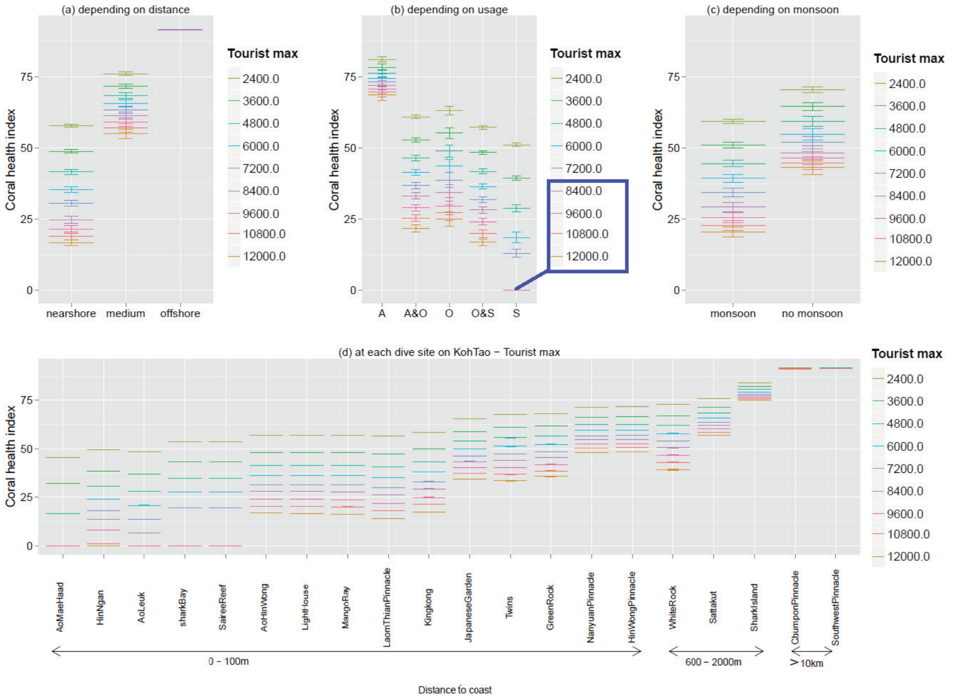


Figure 5.1: Coral health index response to high and low tourist max scenarios at dive sites grouped according to (a) distance from the coast (nearshore, medium and offshore), (b) dive type (A: advanced SCUBA; O: open water SCUBA; S: snorkeling) and (c) whether or not they are influenced in monsoon season, and (d) at all dive sites ranked according to their distance to coast. The configuration growth rate value was 2400.

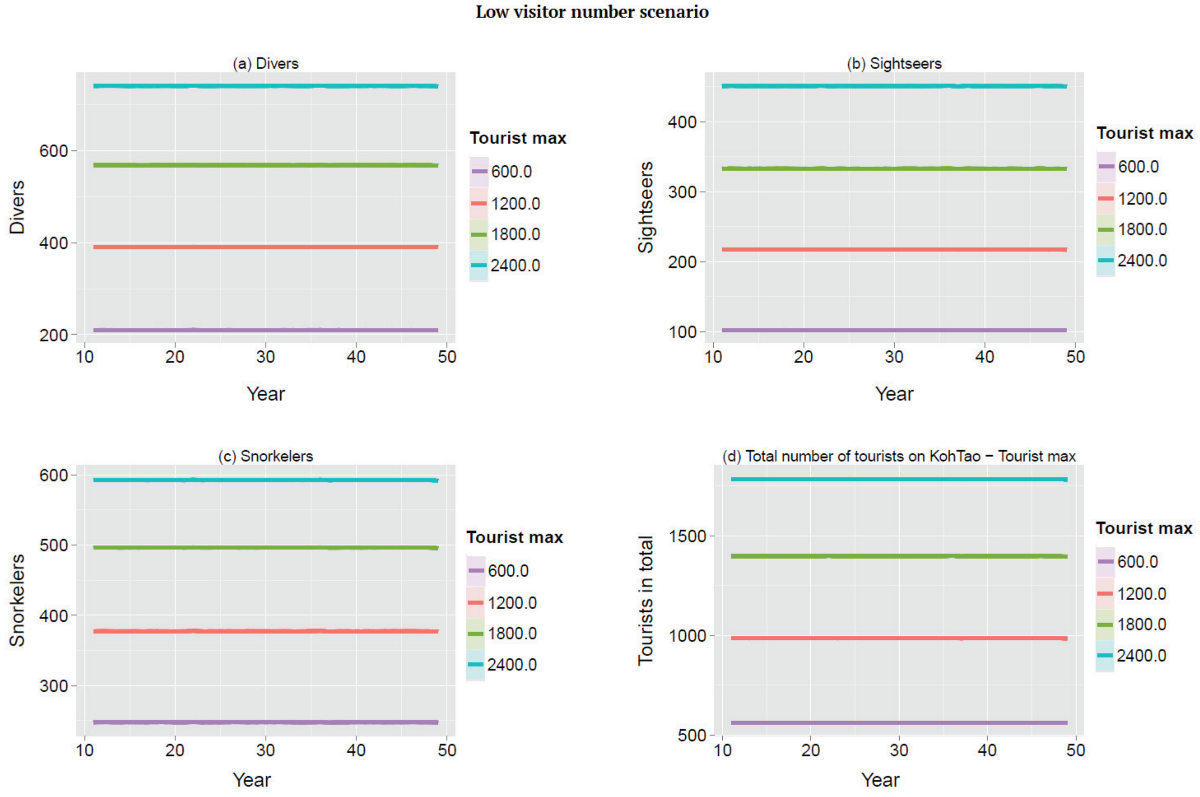


Figure 5.2: Changes in tourist numbers in relation to decreasing tourist max: (a) SCUBA divers; (b) sightseers (c); snorkelers (d) all tourists. Lines show means and the shaded areas standard errors from 20 simulation runs. The configuration tourist max value was 2400 (blue line); in tests this value was decreased in 25% decrements to 800 (green), 1200 (red) and additionally at 600 (red).

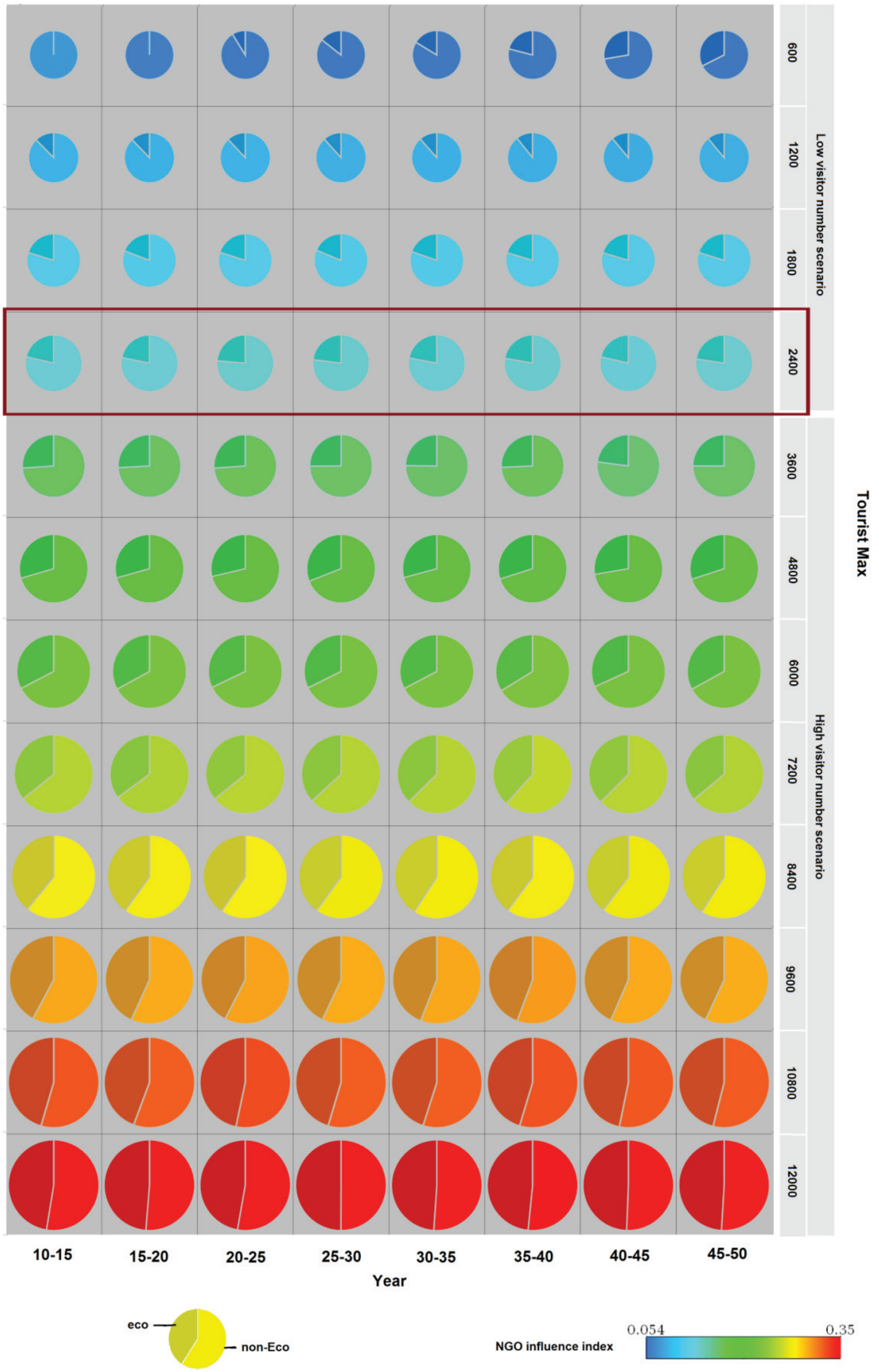


Figure 5.3: Effects of changing the tourist max in 5-year time periods over the course of the simulation, showing the average annual income of all dive schools (size of pie), the NGO influence index (color of pie), and relative proportion of total dive schools income received by eco- and non-eco dives schools (segments of pie). The standard configuration situation is outlined in red.

Presentations

1. Wang Fei (2013). An agent-based model on the effects of dive tourism on Koh Tao, Thailand: Using computer simulation as a sustainable tourism management tool. *ASLO 2013 Aquatic Sciences Meeting* on 20 of Feb in 2013, New Orleans, U.S.A..
2. Wang Fei (2014). Agent-based model on the effects of dive tourism in coral related social-ecological system. *IMCC 2014* on 22 of April in 2014, Glasgow, Scotland.

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I must first thank PD Dr. Hauke Reuter for his expert guidance as my advisor. It was his introduction to agent-based modeling that set me onto this path. It was his reminder to “keep a model as simple as possible and as complex as necessary" that kept me from getting lost in a modeling maze. Discussions with co-supervisor PD Dr. Marion Glaser, committee members, Prof. Dr. Juliane Filser, Prof. Dr. Matthias Wolff, Jennifer Rehren and with my colleague/friend Dr. Robert Katikiro, Dr. Micaela M. Kulesz and Jun.-Prof. Dr. Björn Vollan each with a view unique to their respective disciplines, expertly guided my cross-disciplinary approach.

The support of the Department of Marine and Coastal Resource (DMCR) in Thailand, Save Koh Tao community, New Heaven dive school, CoSea, Koh-Exist and others are much appreciated. Without your help, I would never have survived my field work. The IT department of ZMT & University of Bremen (in particular, Juan Andres Toro and Christoph Lutz) never failed me with technical solutions. It is very important to mention Olaf Thormann, who is both my friend and a guide in Java, leading me through the simplest and hardest of programming issues. Without the professional java optimization from Dennis Gravel, my model would probably still be running and occupying processing resources in the ZMT cluster to this day. I am in debt to Tobias Mildenberger for his fantastic R package and Andrew Halliday for his great English proof editing work. Furthermore, the staff of ZMT and colleagues who hitherto accompanied me are appreciated.

The hard work would not have been possible without support from my family and friends, especially my husband Jan Simon Scherwitzki who has encouraged me throughout my studies with sacrifices, tolerance and compromises in our family life; he and our daughters are the meaning to my life. My mother Xu Hua Xia, my aunt Xu Xiao Qing, my uncle An Qi, the entire Family Scherwitzki, Family Maerkl, Family Chen, Family Rust/DiDomenico, Family Wang, Family Deng/Ma, Family Li/Ding and all my friends (e.g. Li Zhen and Guo Miao) who served as my unofficial advisors in life. I am grateful to you all.

Name: Wang, Fei

Anschrift: Hogenkamp 45 a
26131 Oldenburg

Erklärung

Hiermit erkläre ich, dass ich die Doktorarbeit mit dem Titel:

“Agent-based model on the effects of dive tourism in coral related social-ecological system”

selbstständig verfasst und geschrieben habe und außer den angegebenen Quellen keine weiteren Hilfsmittel verwendet habe.

Ebenfalls erkläre ich hiermit, dass es sich bei den von mir abgegebenen Arbeiten um drei identische Exemplare handelt.

Bremen 16,06,2016

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(Unterschrift)