Addressing socio-ecological problems in the coastal zone of Southeast Asia using system dynamics

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Abstract

In SE-Asia, coastal ecosystems provide many services to communities, including the provision of food, protection from storms and pollution, as well as recreational and tourism services. These coastal ecosystems, and the services they provide, are under threat across SE-Asia due to rapid population growth and development. Many socio-ecological problems have arisen as a result. Examples of these are fish catch decline, mangrove loss, water pollution and food insecurity.

In this paper we describe work being undertaken in the Capturing Coral Reef and Related Ecosystem Services (CCRES) project, a Global Environment Facility, World Bank and University of Queensland funded project. This work is using systems thinking and system dynamics, along with community engagement, to understand why these socio-ecological problems occur and what can be done to address them.

The project is only half complete, however our results to date show that systems thinking and systems dynamics are useful methods for addressing socio-ecological problems. Success depends on using appropriate tools and processes to engage the community and package models in ways that are accessible to most people. We have and are developing Apps and scripts for this purpose, for both data capture and for model delivery, which demystify systems thinking and systems dynamics and facilitate its use in socio-ecological problem solving.

Introduction

Many communities in SE-Asia are dependent on coastal ecosystem services for food and their livelihood. This is indicated by the disaggregated global statistics for fisheries and aquaculture (FAO, 2016) that show SE-Asia dominating in primary (fishers) and secondary (processing, trading) fishing sectors. Fish is also an important source of animal-based protein throughout SE-Asia, exceeding 50 percent of total animal protein in Bangladesh, Cambodia, Indonesia and Sri Lanka (FAO, 2016).

Beyond the provisioning of food, additional services provided by coastal ecosystems include other provisioning (e.g. fuel and timber from mangroves), regulating (e.g. assimilation of pollutants and coastal protection services provided by mangroves), supporting (e.g. nutrient cycling and primary production) and cultural (e.g. recreational and tourism services provided by coral reefs, beaches) services. However, the integrity of coastal ecosystems and the
services that they provide are in decline. Rapid population growth and development occurring across SE-Asia (Jones, 2013) has resulted in increased demand on local resources, such as seafood (FAO, 2016), water (Howes and Wyrwoll, 2012) and mangroves (Brander et al., 2012). It is also driving change in catchment land-use patterns (Ardli and Wolff, 2008) and increasing waste production (Howes and Wyrwoll, 2012), which can lead to loss of habitat (Ardli and Wolff, 2008) and overwhelm the regulating capacity of coastal ecosystems (Beier et al., 2015).

These cascading impacts on coastal ecosystems have caused a number of problems in the SE-Asia region that threaten the well-being and livelihoods of many coastal communities. Of these, declining mangrove habitats (PCSDS, 2006a; Brander et al., 2012), along with overexploitation of fisheries (Hatzios, 2013; FAO, 2016), coastal water pollution (PCSDS, 2010) and food insecurity (Aguila et al., 2016) have emerged as prominent examples.

Solving these problems is not simple because they are the result of interactions between ecosystems, economies and societies, making them socio-ecological problems. Socio-ecological problems arise from the relations between dynamic ecosystems and the many scales of social networks (e.g. fishers, households, regional institutions) that interact with them (Murray et al., 2006). They are often framed as ‘wicked’ problems (Davies et al., 2015), or as the stakes are raised, as ‘super wicked problems’ (Lazarus, 2009) and are characterised by multiple spatial (local, regional, national and/or international) and temporal (e.g. days, weeks, months, decades) scales, multiple dimensions (e.g. social, ecological, economics, political), complex interactions, feedback pathways and conflicting stakeholder interests (Sterman, 2000).

To address the complexities of socio-ecological problems, we apply systems thinking and system dynamics to understand how the interactions between ecosystems, economies and societies lead to their development. This is distinct from the common reductionist approach to handling complex problems, which breaks the system into component parts and ignores the role of feedbacks. We also apply a participatory process that enables us to draw upon the pool of local knowledge and build ‘public constituency’ for addressing the root causes of socio-ecological problems (Hovmand, 2014).

We have applied our systems analysis process to two locations within SE-Asia: El Nido, located in the Philippines, and Selayar, located in Indonesia. The aim of this analysis is to understand how communities currently use and interact with coastal ecosystems (i.e. coral reefs, mangrove forests, seagrass beds) and how these interactions, along with external factors, have led to current problems such as fish catch decline, mangrove loss, water pollution and food insecurity.

This systems analysis is an activity of the Capturing Coral Reef & Related Ecosystem Services (CCRES) project (www.ccres.net). CCRES is a Global Environment Facility (GEF), World Bank (WB) and University of Queensland (UQ) funded project, primarily focused on enhancing livelihoods and food security, improving community health and wellbeing, and sustaining ecosystems in the coastal zone.
Study Area Description

*El Nido, Palawan, Philippines.*

The Municipality of El Nido (Figure 1) is located in the northern part of the province of Palawan, Philippines. It is bounded to the north by the Linapacan Strait (Luzon Sea), the east by Taytay Bay (Sulu Sea), the south by the municipality of Taytay and to the west by the South China Sea (PCSDS 2006b; Aguila et al., 2016). El Nido has a land area of 923 km², consists of 18 rural political subdivisions (Barangays), four of which are classified as urban and 14 classified as rural (Aguila et al., 2016). The main land uses are forestland (32%), agriculture (34%) and built-up (17%) area (Aguila et al., 2016).

Salient environmental issues that have been identified for El Nido include the depletion of marine resources and mangroves, land development and “inefficient implementation of zoning standards resulting in urban congestion” (PCSDS, 2006b). These issues (and concerns about these issues) have been exacerbated by recent changes in population dynamics.

Census data for El Nido (PSA, 2016) indicates rapid population growth (Figure 2a) for the Municipality. Anecdotal evidence indicates that the population growth (and concomitant development) rate has increased markedly since 2011 on the back of a strong increase in tourist numbers (Figure 2c). At the same time, there has been a decline in traditional sources of local food, such as fishing (Figure 2b) and agriculture (Aguila et al., 2016).

![Figure 1: Municipality of El Nido, Palawan, Philippines (red pin marks the location).](image-url)
**Kabupaten Kepulauan Selayar, Indonesia**

Kabupaten Kepulauan Selayar (Selayar) (Figure 3) is one of the Kabupaten in South Sulawesi Province. It is bordered by the Bulukumba Regency to the north, Flores Sea to the east, Flores Sea and Makassar Strait to the west and Nusa Tenggara Timur Province to the south. Selayar is comprised of 11 Kecamatan or sub-districts with a total land area of 1,357 km$^2$ (BPS Selayar, 2014a), consisting of 130 islands, 34 of which are inhabited (Adrianto et al., 2016).

Selayar’s current population (as of 2015) is 128,744 (BPS Selayar, 2015b) with recent annual growth rate (2010 – 2014) at ca. 1.04% (BPS Selayar, 2015a). The most populated sub district is Kecamatan Benteng, which has 23,811 inhabitants.

Coral reef fishing is a common livelihood in Selayar. The number of fishers has increased over the period 2010 and 2014 (Figure 4a) (BPS Selayar, 2015a). During the same period the total fish catch doubled from 15,000 to 30,000 tonnes (Figure 4b) (BPS Selayar, 2015a).
Most of the fishers are traditional, characterised by their limited skill and fishing gear (Adrianto et al., 2016). Fishing boats are typically small and mostly equipped with small motors that restrict their fishing range to near shore (Adrianto et al., 2016). As a result, fishermen in Selayar rely heavily on localised coral reef fisheries (Adrianto et al., 2016).

Anecdotal information emerging from the scoping visits indicate that the integrity of the reefs surrounding Selayar have been compromised by illegal destructive fishing activities (i.e. bomb and cyanide fishing). This reflects a national concern that Indonesian reefs are at increasing risk from a range of local stressors including destructive fishing (Hatziolos, 2013).
Methods

In this study, we follow the five main steps in the systems modelling process: 1) problem articulation, 2) formulation of a dynamic hypothesis, 3) formulation of a simulation model, 4) simulation model testing, 5) policy design and evaluation (Sterman, 2000). These steps, along with the activities conducted in each, are summarised in Table 1.

Table 1: Methodological steps followed in this study (FGD = Focus Group Discussions).

<table>
<thead>
<tr>
<th>Steps</th>
<th>Activities</th>
<th>El Nido</th>
<th>Selayar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem articulation</td>
<td>Workshops</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Scoping visit</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>System specification (formulation of dynamic hypothesis)</td>
<td>Creation of Core Modelling Teams</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>FGD Training</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>FGD Round 1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>FGD Round 2</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Simulation modelling</td>
<td>Model specification</td>
<td>Underway</td>
<td>Underway</td>
</tr>
<tr>
<td></td>
<td>Data collation</td>
<td>Underway</td>
<td>Underway</td>
</tr>
<tr>
<td></td>
<td>Model testing</td>
<td>To be done</td>
<td>To be done</td>
</tr>
<tr>
<td>Policy design and evaluation</td>
<td>FGD Round 3</td>
<td>To be done</td>
<td>To be done</td>
</tr>
<tr>
<td>Decision support tool delivery</td>
<td>Tool design</td>
<td>To be done</td>
<td>To be done</td>
</tr>
<tr>
<td></td>
<td>Tool development</td>
<td>To be done</td>
<td>To be done</td>
</tr>
</tbody>
</table>

Problem articulation

The focus problems were identified using both workshops and scoping visits.

In El Nido, Palawan State University (PSU) had already conducted a community survey from which problems could be identified (PSU, 2013). Consequently, a workshop was conducted at PSU in late 2014 with the objective of selecting a suite of priority problems from which the focus problems were drawn. Workshop participants were from PSU, the Palawan Council for Sustainable Development (PCSD) and the El Nido Foundation (ENF). During the workshop participants were asked to rank problems identified by the PSU community survey from most to least important. For the top four problems, participants were asked to complete a stakeholder map containing four quadrants: stakeholders directly and indirectly affecting the problem, and stakeholders directly and indirectly affected by the problem.

For Selayar, a scoping visit was conducted in 2015 to elicit problems from villages. The main participants in each of the village meetings were fishermen and their wives, fish traders, community leaders, local extension agents and local government officers. The process used in each visit was as follows:
- Participants were asked to draw a map of their village on flip chart paper and on the map locate activities conducted by village members (such as fishing) and resources used (such as coral reefs).
- Participants were then asked to draw trend graphs for these activities and resources over the last 5 to 10 years (have fish been increasing or declining, for example).
- From these trend graphs participants were asked to identify problems, that is, which trends did they consider to be problematic.
- Participants were asked to rank these problems from most to least important.
- For the top three problems, participants were asked to complete a stakeholder map containing four quadrants: stakeholders directly and indirectly affecting the problem, and stakeholders directly and indirectly affected by the problem.

System specification

Once focus problems were identified, core modelling teams (CMTs) were established to conduct focus group discussions within villages for each problem (FGDs). Each CMT was comprised of four people / roles:

- Facilitator: responsible for managing the FGD discussion and engaging participants
- iPad Driver: uses SESAMME to record information provided by participants (SEAMME is described latter in this section)
- Documenter: responsible for note taking and recording
- Runner: provides the other roles with assistance when necessary

Each CMT conducted two rounds of FGDs. The purpose of each round was as follows:

- Round One: Capture the mental models of participants about the activities, resources and pressures related to a specific problem (individual FGDs focused only on one problem); the past, expected future and desired future trends of these activities, resources and pressures; the interactions among these activities, resources and pressures and the polarity of these interactions (positive or negative); any decisions/interventions that could influence the future trends in activities, resources and pressures. The mental models were captured in the form of rich pictures (similar to causal loop diagrams).
- Round Two: Mental model update, review and learning from the mental models of others. Before this round was conducted, the results from the first round were compiled and used to identify any commonly occurring themes. Edits were then done to the rich pictures produced by each FGD, and the edited rich pictures taken back to the same people that participated in round one for review and comment.

Both FGD round one and two were conducted according to a script, which is a logical and repeatable process that allows the results of multiple FGDs to be compared. SESAMME, a purpose built iPad App (beta version), was also used within the FGDs. SESAMME allows the activities, resources and pressures, their trends and interactions, and decisions, to be recorded on a map (see Richards et al. 2016, for a description of SESAMME). Based on the
FGD results, conceptual models in the form of causal loops diagrams were developed for each focus problem.

**Simulation modelling**

The conceptual models formed the basis of simulation model development. The main themes in the conceptual models were used to identify sub-models. Stock and flow models are currently being developed using Stella® for each of the sub-models. The sub-models include:

- Catchment runoff (volume as well as concentrations of N, P and sediment)
- Wastewater (volume as well as concentrations of N, P and sediment from septic tanks and stormwater)
- Crop and Livestock production
- Fish production (for herbivore and predator reef fish as well as squid)
- Fishing (traditional, bomb and poison fishing)
- Coastal habitat (amount and condition of coral reefs, sea grass and mangroves)
- Land use change (as a result of crop and livestock expansion, and urban expansion)
- Human population (both domestic and tourist)
- Price (for crops, livestock and fish)
- Water consumption (for crops, livestock and human population)

These sub-models link together to form one integrated socio-ecological system model. The structure of the models for both El Nido and Selayar will be the same, the parameters used will be site dependent. This means that the model structure will be transportable to other sites, however the parameters will be site-specific.

Secondary data is currently being collated from previously conducted bio-physical and socio-economic surveys to parameterise the sub-models. Once this is complete the models will be tested using (a) structural tests that determine whether the structure of the model is an adequate representation of the real system, and (b) behaviour tests that determine whether the model is capable of producing an acceptable output behaviour. The structural tests will consist of feedback loop tests, conservation of matter tests and negative stock tests. The behaviour tests will include a comparison of modelled trends with historical trends and extreme conditions tests.

**Policy design and evaluation**

After testing, the integrated socio-ecological system model for El Nido and Selayar will be used in a third round of FGDs. The purpose of this round will be to explore scenarios and test if interventions can shift the future trajectory of the focus problems in a favourable direction. FGD round three will be conducted with the same people that participated in rounds one and two. It will also be conducted according to a script that explores:

- A base case scenario that represents the current situation
• A best case scenario that promotes sustainable development
• A worst case scenario that does not promote sustainable development
• Two intermediate scenarios that represent alternatives between the best and worst case

FGD participants will also have the opportunity to specify three of their own scenarios. All scenarios will be run to the year 2050. The results from these scenario runs will be compared using a multi-criteria analysis tool called Facilitator (https://sourceforge.net/projects/facilitator/?source=directory). This will account for stakeholder preferences and help to identify those scenarios that are most commonly preferred among stakeholders.

Decision support tool delivery

The integrated socio-ecological system model will be quite complex, restricting its use to those with technical modelling skills. This limits its potential use by policy makers within local, provisional and federal governments and by NGOs or private enterprise. To overcome this limitation, we will develop SYSTORY, a system storytelling and decision support App. The storytelling component of SYSTORY will teach users about the system and why the focus problems occur using a cartoon interface. The story will be organised into chapters, one for each focus problem. The decision support component of SYSTORY will allow users to explore scenarios and the effect of decisions on the future trajectory of the focus problems. SYSTORY will be available for both Apple and Android devices and will be capable of running on tablets and phones, meaning that people will be able to use our system models without the need for expensive computers or software.

Results

Problem articulation

Four focus problems were identified for El Nido and one for Selayar. These were:

• El Nido: Fish catch decline, food insecurity, mangrove loss and water pollution
• Selayar: Coral reef fisheries decline

A photograph taken at one of the village scoping visits conducted in Selayar is shown in Figure 5. An example of a village map drawn at one of these scoping visits is shown in Figure 6.
Figure 5: Village scoping visit in Selayar, Indonesia.

Figure 6: Village map drawn during the village scoping visits in Selayar (the map identified activities conducted by the village, such as cropping, grazing and fishing, and the resources used).
**System specification**

The CMTs assigned to each focus problem are summarised in Table 2. The number of FGDs conducted and the number of participants attending the FGDs are summarised in Table 3.

**Table 2: Focus problems and core modelling teams.**

<table>
<thead>
<tr>
<th>Problem</th>
<th>Core modelling team</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish catch decline</td>
<td>Palawan State University (PSU)</td>
</tr>
<tr>
<td>Food insecurity</td>
<td>El Nido Foundation and PSU</td>
</tr>
<tr>
<td>Mangrove loss</td>
<td>Palawan Council for Sustainable Development (PCSD)</td>
</tr>
<tr>
<td>Water pollution</td>
<td>PSU</td>
</tr>
<tr>
<td>Coral reef fisheries decline</td>
<td>Bogor Agricultural University (IPB)</td>
</tr>
</tbody>
</table>

**Table 3: Number of FGDs and FGD participants in El Nido and Selayar**

<table>
<thead>
<tr>
<th>Activity</th>
<th>El Nido</th>
<th>Selayar</th>
</tr>
</thead>
<tbody>
<tr>
<td>FGD Round 1</td>
<td>88</td>
<td>17</td>
</tr>
<tr>
<td>FGD Round 2</td>
<td>44</td>
<td>17</td>
</tr>
<tr>
<td>Participants</td>
<td>1000+</td>
<td>300+</td>
</tr>
</tbody>
</table>

A photograph from one of the FGDs conducted in El Nido using the SESAMME App is shown in Figure 7. A SESAMME map produced during a first round FGD in Selayar is shown in Figure 8.

**Figure 7:** FGD conducted in El Nido (SESAMME is projected on the screen during the FGD)
Figure 8: SESAMME map produced during a fist round FGD conducted in Selayar (the map depicts activities, resources, pressures, their trends, interactions and polarities).

An example of the analysis conducted using the SESAMME maps is shown in Figure 9. The conceptual model (causal loop diagram) created as a result of the FGDs conducted in Selayar is shown in Figure 10.

Figure 9: An example of SESAMME map analysis (This example shows that across 22 SESAMME maps, 86% identified an interaction from coral to fish and 59% identified an interaction from fish to coral).
Figure 10: Conceptual model (causal loop diagram) created for coral reef fisheries decline problem in Selayar (the model depicts activities, such as fish bombing and poison fishing, resources, such as coral and coral fish, and pressures, such as human population and bomb suppliers, that were identified during FGD rounds one and two).
**Simulation modelling**

An example of the stock and flow sub-model developed to model fish population dynamics is shown in Figure 11. This model simulates the population of juvenile and adult fish (both herbivores and predators) and the effect of coral reef condition and fishing intensity on these fish populations. The model essentially covers the coral fish, coral fishing and coral variables in Figure 10. Coral reef condition affects the carrying capacity of coral reef fish (both juvenile and adults) as well as the recruitment of juvenile fish, while fishing intensity (catch rate) affects the adult fish population and the recruitment of juvenile fish. The behaviour of the fish population sub-model shows that as fishing intensity is increased, the adult fish population is reduced, which also reduces the juvenile fish population though reduced recruitment (Figure 12a). The fish catch initially increases as fishing intensity increases and then peaks. As fishing intensity increases further, the fish catch declines again (Figure 12b). The point at which fish catch peaks is the maximum sustainable yield of the fishery, which in this example is a catch rate of 20% of the adult fish population (line 3 in Figure 12b).

![Figure 11: Stock and Flow sub-model for simulating juvenile and adult fish populations according to coral reef condition and fishing intensity.](image)

*Figure 11:* Stock and Flow sub-model for simulating juvenile and adult fish populations according to coral reef condition and fishing intensity.
Figure 12: Adult herbivore fish population (a) and adult herbivore catch (b) for 11 different fishing intensities (from an adult population catch rate of 0% (line 1) to 100% (line 11), increasing in 10% increments).

The main feedback loops that exist between the sub-models within the integrated socio-ecological system model are shown in Figure 13. The colours in this diagram represent the stage of development of each sub-model (green = complete, orange = partially complete, red = to be done).
Figure 13: Main feedback loops between sub-models within the integrated socio-ecological system model.
Decision support tool delivery

The development of SYSTORY, the delivery mechanism for the integrated socio-ecological system model, has not started, so we use an example produced by BTN below to show what the tool will look like (www.learnwithbtn.com). SYSTORY will allow users to enter a story, go directly to the model for scenario analysis, or enter a question and answer section to test their knowledge (Figure 14).

![SYSTORY main menu](image)

**Figure 14:** Example of the SYSTORY main menu.

The storytelling interface will be split into chapters (one chapter for each focus problem) and each chapter will guide users through a cartoon style description of the system (Figure 15). As the user steps through a story, the interface will zoom in to that particular part of the system, explaining how it works using text and narration (Figure 16). The model interface will allow users to open a set of controls for scenario analysis (Figure 17) and view the results of any particular scenario as graphs over time (Figure 18). The scenario analysis interface will set the limits of each control and will determine those variables that the user can change in the model.
Figure 15: Example of the storytelling interface of SYSTORY.

Figure 16: Example of how SYSTORY will step users through the story using text and narration.
Figure 17: Example of the scenario analysis interface in SYSTORY.

Figure 18: Example of the scenario results graphs produced by SYSTORY.
Discussion

Our results so far highlight the usefulness of systems thinking method, combined with community engagement, in addressing socio-ecological problems in the coastal zone. However success depends on using appropriate tools and processes to engage the community. We used core modelling teams consisting of local people to engage the community in the process. We also trained our teams in system thinking method, and developed tools (such as SESAMME) and scripts for them to facilitate the engagement process. The training, tools and scripts were also important for ensuring that the data collection between FGDs and among the teams was consistent. Having said this, we did find that some FGDs wandered away from the focus problems, highlighting the importance of good FGD facilitation to keep participants focused.

The success of SESAMME in helping to engage stakeholders has meant that members of our core modelling teams have begun to use it beyond our current project. To facilitate the broader use of SESAMME, we intend to make it customisable, allowing users to import their own icons and establish their own icon categories.

Our simulation models are still under development, however we have had a positive reaction from those that we have shown our SYSTORY example to. The key advantages of SYSTORY are that it demystifies system dynamics for non-technical people, it allows users to learn through storytelling rather than just running scenarios, and because you only need a phone to use it, it is low cost and accessible to most people. The particular advantage of using system dynamic models in our study is that they have allowed us to model generic processes. For example, the simple fish population model shown in this paper can be transferred to other locations because it models the generic processes of fish recruitment, carrying capacity and fish catch. The initial values in the system dynamic models must be set for a location, so some data collection is necessary before the models can be used outside of the locations for which they have been parametrised.

We also learnt that it is important to include capacity building into any project utilising systems thinking or system dynamics methods. We did this with our core modelling teams by training them in systems thinking and system dynamics as part of the project, rather than just using them as data collectors. This did two things. It gave them a reason to be involved in the project plus it will allow them to use systems thinking and system dynamics beyond the life of the project and apply systems methods to new problems.

Acknowledgements

We would like to thank the Global Environment Facility, World Bank and University of Queensland for funding the CCRES project. We would also like to thank our local partners and members of our core modelling teams in the Philippines and Indonesia for helping us to implement the project. Finally we would like to thank the community of El Nido and Selayar for their willingness to participate in the project and the knowledge that they have provided.
References


