Analysis of Environmental Sustainability by Causal Loop Diagram and System Dynamic Model - A Case of the Great Barrier Reef

Runze Ding¹, ², *

¹ UQ Business School, the University of Queensland, Brisbane, Australia
² General Manager Office, Koala International Pty., Ltd., Brisbane, Australia

* Corresponding author e-mail: runze.ding@uq.net.au

Abstract. The booming tourism industry has always played a vital role in the Australian economy. However, with the influx of tourists, the ecological environment of many scenic spots has been destroyed. As one of the typical areas in Australia, the Great Barrier Reef is suffering an increasing number of coral death due to natural disasters and man-made destruction. This study identifies the key variables and estimates the data collected from multiple channels, through building causal loop diagrams and system dynamic model to specifies the logic relationship between different variables and impact factors, and then further quantify their effects and analyze the interplay of them to clarify how they affect the ecological environment and business development of the Great Barrier Reef. The running results of the system dynamic model are consistent with the actual situation of the Great Barrier Reef, it provides a tangible future prediction of the Great Barrier Reef and puts forward the point that if the governments fail to take effective intervention measures, the mortality rate of coral reefs will continue to increase until they disappear completely in a few decades.

Keywords: Causal loop diagram, System dynamic model, The Great Barrier Reef, Environmental protection, Business and tourism development.

1. Background

As one of the imperative economic pillars of Australia, the developed tourism industry attracts millions of international tourists, with the number of arrivals reaching 9.25 million in 2018 [20]. A large number of tourists not only promote the local economy, but also conduce to the development of the local employment, company trade, infrastructure construction, etc. For example, between 2015 and 2016, the Great Barrier Reef, one of the famous tourist attraction in Australia, contributed $6.4 billion (AU dollars) and 64,000 jobs to Australia, accounting for 45.3% and 37.5% of the total contributions of the national tourism industry of Australia respectively [5]. However, the negative impact of tourism has seriously damaged the local ecological environment. As the world's largest coral reef system, the Great Barrier Reef is facing a worsening issue - coral bleaching. Researches have shown that in the northern and central areas of the Great Barrier Reef, where the most heavily visited areas, 81% and 33% of corals have been severely bleached respectively [3]. Even many studies point out that the Great Barrier Reef
will disappear completely in the future [1]. Therefore, it is vital to understand what factors and to what extent those factors affect the ecological environment of the Great Barrier Reef. This study establishes the dynamic system model based on Vensim PLE and Stella Architect tools and analyzes the impacts of different variables on the Great Barrier Reef through building casual loop modelling, fundamental modes of dynamic behaviour, system archetypes and dimensionless multipliers, thereby analyzing how different factors impact on the Great Barrier Reef and provide effective prediction to the change of its future environment and the tourism business development.

2. The key variables and stocks

2.1. Coral population
Since 1980, coral bleaching on the Great Barrier Reef has become more and more serious. The 2016 figure shows that the amount of surface coral in the Great Barrier Reef area has fallen to less than 35% of its 1980 level. Besides, half of the Great Barrier Reef has been bleached to death since 2016 [7]. It is a vital dependent variable that can quantify the effects of other variables.

2.2. Annual number of tourists
The number of visitors to the Great Barrier Reef has been growing year by year, from approximate 1.6 million in 2008 to more than 2.3 million in 2018 [19]. It is a vital independent variable that can further affect the amount of coral damage.

2.3. Local GDP (Cairns)
Tourism on the Great Barrier Reef is geographically concentrated, with 85% of tourist visitation taking place in the Cairns [17]. Thus, Cairns, a city in northern Queensland, Australia, is selected as the object to analyze economic data. Also, figures show that the GDP and GRP growth rates of Cairns were both higher than those of Australia. The change in GDP will directly affect the government's investment in coral conservation and thus affect the coral population.

2.4. Number of infrastructures
The infrastructure refers to tourism-related infrastructures and buildings, including pontoons, hotels, amusement parks, wharf, etc. The study draws up the amount of infrastructure and other related information based on the data from various news, government reports, documents and reasonable assumptions. The amount of infrastructure affects the number of tourists through affecting the attraction of scenic spots to tourists, it also directly affects the number of corals through developing the pristine area into a commercial area.

3. The Causal Loops Diagram of the Great Barrier Reef

3.1. Structure and Behaviour
The causal loop diagram (CLD) is used to qualitatively model the causal relationships among a set of variables in a system, it captures our dynamic hypothesis and communicates important feedback loops. The arrows indicate cause-and-effect relationships between pairs of variables, when two variables are related in a CLD, we indicate the relationship between them by the different “polarity”. The two variables move in the same direction, that is, as the cause goes up the effect increases above what it would otherwise have been: this is indicated by a “+”. In contrast, when the two variables move in opposite directions, that is, as the cause goes up the effect decreases below what it would otherwise have been: this is indicated by a “−”. Meanwhile, CLD uses feedback loops to represent a chain of effects that can be traced back to the original cause. Reinforcing or positive feedback loops indicated by an “R” while balancing or negative feedback loops indicated by a “B”. Over time, strengthening the feedback loop will amplify changes within the system, also known as a vicious circle and a virtuous circle [9,13].
Based on it, this study establishes a CLD to show the causality between variables, divides the CLD into several parts, and selects two cores for detailed analysis.

3.1.1. The number of tourists loop. As shown in figure 1, a typical reinforcing and balancing loops can be found respectively in the logical relationship. We can found that the increased number of tourists, on the one hand, contribute to tourism consumption and local economic income, thereby increasing tourism income and leading to more infrastructures being built, and the development of infrastructure will ultimately benefit the increase in the number of tourists. On the other hand, it leads to a high coral mortality rate. Coral mortality rate and coral population are negatively correlated, while the coral population and the Great Barrier Reef’s attractiveness to tourists are positively correlated. Besides, some other variables, including ocean heat waves, local activities and coral birth rate also affect the logical relationship.

3.1.2. The coral population loop. As shown in figure 2, there is a positive correlation between the number of polyps and corals population. The artificial planting and survival rate affect the birth of coral polyps while the marine ecological environment affects both the death of coral polyps and coral mortality rate.

3.2. The System Archetypes
System archetypes are generic models that can be used to explain common behaviour in a variety of systems. As diagnostic tools, they provide insight into the underlying structures from which behaviour and cautious events emerge over time. As forward-looking tools, they alert managers to possible unintended consequences in the future [18]. The study selects two key system archetypes to help scholars further clarify the underlying significance under the different loops.

3.2.1. Fixes that Fail. One of the archetypes called “Fixes that Fail”, it represents when the management’s response to the issue is aimed at the rapid resolution of the symptoms rather than the underlying systemic cause of the issue, unintentional and harmful consequences normally appear. As shown in figure 3, expanding more areas of the Great Barrier Reef could help make it more attractive and bring in more tourists. However, in the long term perspective, expanding more areas of the Great Barrier Reef will lead to coral bleaching, which finally leads to a decrease in the number of tourists.
3.2.2. Tragedy of the Commons. The other archetype called “Tragedy of the Commons”, it represents an over-utilization of public pool resources. It occurs when individuals try to maximize their benefit from public resources, however, over time, the over-exploited resources reducing the benefit for everyone using the resources. As shown in figure 4, local and tourist activities increase the total activities which lead to coral bleaching because it exceeds the carrying capacity of the Great Barrier Reef. The coral bleaching impacts the gain of marine resources and the attraction of the Great Barrier Reef, thereby reducing the opportunities for the development of activities.

4. The System Dynamic Model
An obvious limitation of the CLD above is that they do not distinguish between stock and flow, so they cannot be used in quantitative model systems. Thus, establishing a system dynamic model (SDM) can help us to quantitatively model system behaviour over time [12]. In a SDM, there are two key components, stocks and flows. Stock presents a square in the model, its value at any given instant in time depends on how the system has behaved in the past. The stock gives systems memory and inertia and creates delays, thus, we calculate the value of the stock at different particular instants by analyzing the influence from other parts in the systems. Flow presents an arrow in the model, it shows a decrease or increase in a stock that can only be calculated over a period of time. Meanwhile, the shapes of cloud and circle (converters) in the model respectively present the resources outside the boundaries of the model and auxiliary variables included in the feedback loop between inventory and flow [10]. Based on the current data and researches, through combining all the components according to their logical relations, a SDM (Figure 5) can be formed to proceed dynamic analysis and prediction to the future environmental conditions as well as the business and tourism development of the Great Barrier Reef.

As shown in figure 5, there are four key stocks in the SDM, the annual number of tourists, the number of infrastructures, local GDP (take Cairns for example), and corals population. In general, the number of tourists affects the local GDP, which affects the number of infrastructures and the infrastructures, in turn, affects the number of tourists, meanwhile, these three factors also interact with the coral population. Also, there are three key converters, the total number of destroyed corals per year, the attraction of the Great Barrier Reef to tourists and the tourist consumption. These three key converters connect the whole model and show how the variables affect each other.
4.1. The total number of destroyed corals per year
The first key converter is the total number of destroyed corals per year, we estimate it by adding the corals destroyed by infrastructures per year, the corals destroyed by tourists per year and the corals destroyed by local activities.

4.1.1. The number of corals destroyed by tourists & infrastructures per year. By searching for information, including previous researches, news and government publications, the relevant data can be collected. As shown in figure 6, we estimate the total activities related to the Great Barrier Reef and corals destroyed per activity to estimate corals destroyed by tourists per year. For example, by consulting websites from travel agencies and the sources from news, we estimate that the number of activities that each visitor does per day is 4.5, and assumed that half of these activities are likely to cause damage to corals, with an average of 64 for each activity (As an aside, the exact number of corals cannot be calculated, so here we estimate the amount of damage by calculating the total area and average size of the reef). Thus, combined with the number of tourists, we can figure out the rough number of the corals destroyed by tourists per year [4,8,15]. Similarly, as shown in figure 7, the corals destroyed by infrastructures per year can be estimated.
4.1.2. The number of corals destroyed by local activities. As shown in figure 8, through analyzing the data from local activities, including farming, oil spill, etc. to estimate the corals destroyed by local activities. All of these lead to a decrease in the overall coral population. For example, the Great Barrier Reef has an average of 14 oil spills a year, each of which kills 268 million corals, so we can estimates the corals destroyed by oil spill per year [2,6,14]. Besides, an average of 4 ocean heat waves a year also kills a large number of corals directly [12].

4.1.3. The protected corals per year. However, as shown in figure 9, it is worth mentioning that the environmental expenditure from governments at different levels and the investments from other organizations are an obvious benefit to protect the corals. For example, we estimate that one million Australia dollars can protect 71 million corals, then multiply this number by the total expenditures added from two parts, an average 575 million dollars of special protection fund from different levels’ government, such as the central government of Australia, the Queensland state government, etc. and the variable environmental protection expenditure that based on the local government revenue of the year [11, 16]. Therefore, the protection will be quantified and used to reduce the amount of coral lost.

4.2. The attraction of the Great Barrier Reef to tourists & The tourist consumption
As shown in figure 5, the second key converter is an attraction of the Great Barrier Reef to tourists, it depends on the number of corals and infrastructure. According to the mentioned method above that proceed estimation by the available data, we can estimate the attraction of actual corals population and desired corals population to tourists and the data related to infrastructure, so that we can conclude the attraction of the Great Barriers Reef to tourists that directly affects the number of tourists. Besides,
changes in the number of tourists affect their demand for entertainment level, which related to the third key converter, tourist consumption. Thus, we set and quantify the concept, effect of entertainment level on tourists consumption, to bridge this relationship. The increasing number of tourists not only leads to a growing desired entertainment level, but also brings the sequential growth of the number of activities, tourism consumption, GDP and the number of infrastructures. Then, more infrastructures bring more convenience to tourists to stimulate their consumption again. However, the increase in both infrastructure and activities will put pressure on the environment, as a result, more corals will be destroyed.

5. Tendency prediction

Figure 10 shows the number of destroyed corals from three aspects. The number of destroyed corals showing a growing trend before 2030 then start to decrease. As the reason shown in figure 11 & 12, with time goes on, fewer corals make them less attractive, leading to a drop in tourist numbers, GDP and infrastructure. Thus, destroyed corals from these aspects decrease.

Figure 10. Number of destroyed corals

Figure 11. GDP and number of tourists

Figure 12 shows the number of corals keeps on decreasing. Before 2025, the attraction of the Great Barrier Reef to tourists increases, however, after 2025, when the number of corals drops to less than desired corals by tourists, the attraction begins to decrease rapidly. Meanwhile, figure 13 shows low attraction leads to fewer tourists and less spending, which leads to lower GDP and less infrastructure. As a result, after a few short years, a drop in the number of infrastructures further reduces the attraction of the Great Barrier Reef.

Figure 12. The Great Barrier Reef’s attraction

Figure 13. Infrastructure’s attraction

Figure 14 & 15 show the reasons of the decrease in total tourist consumption and revenue. On the one hand, the decrease in the number of infrastructures leads to a decrease in convenience, which leads the tourists do not want to spend their money even fewer opportunities for them to spend their money.
On the other hand, the decrease in the number of tourists means a decrease in activities, which results in a decrease in the level of entertainment required by tourists, which also leads to less tourism consumption.

![Figure 14. Convenience and infrastructures](image1)

![Figure 15. Desired entertainment level](image2)

6. Conclusion

This study selects the business and tourism development as well as ecological environmental protection (coral bleaching) issues of the Great Barrier Reef in Australia as the context, realizing the dynamic analysis of the interaction of multiple variables through establishing CLD and SDM. Based on analyzing the data of the Great Barrier Reef between 2010 and 2020 to predict its future changes between 2020 and 2050. The SDM provides an effective prediction, its running result is consistent with the actual situation that several researched and predictions indicate that, due to natural disasters and man-made destruction, the Great Barrier Reef currently at a critical tipping point and could disappear in the next few decades [1, 21]. However, the main limitation of this study is that the data of the variables are not accurate even if they conform to the overall trend. Some variables are quantified based on rough estimates of basic data, which leads to uncertainty in the conversion of units between variables. For example, we cannot calculate exactly how many coral reefs per square kilometre and how many corals a coral reef contains. Thus, a fruitful avenue for future research would be to apply more precise methods for collecting and calculating data.

The practical implication of this study lies in that it clearly points out the interaction and logical relationship between different variables and quantifies the impact of them on the ecological environment of the Great Barrier Reef. This study analyzes the multiple impact factors and plays a role of learning for subsequent studies, it not only helps to warn tourists to reduce their improper behaviour that might lead to irreversible negative consequences to the local ecology, but also conduces to guide the governments and organizations to implement effective intervention measures to protect the environment of the Great Barrier Reef and stop the vicious circle, finding the balance between tourism business management and environmental protection as well as achieving sustainable development by controlling the impacts of different variables.

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