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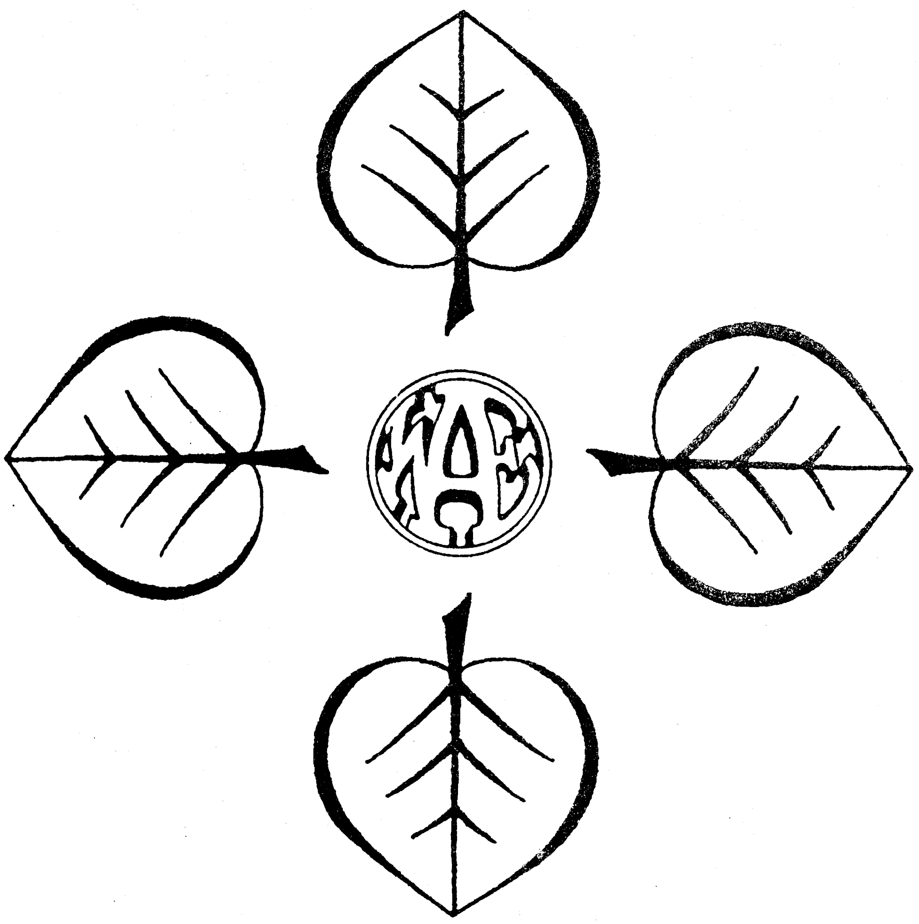

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Optimal Use Management of a Coral Reef: A Study of Hanauma Bay, Hawaii

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Abstract

Hanauma Bay is an underwater state park in Hawaii exhibiting the classic problems of a common property resource. Long term heavy use and severe environmental degradation have elicited recent legislative action. Efficient park management, however, is confounded by a lack of information about the critical functional relationships. This research develops a control model for managing a coral reef ecosystem to guide future legislative efforts.

Background

Approximately 50,000 years ago a series of volcanic explosions broke through the sea wall of a volcanic crater. Sea water entered the crater and Hanauma Bay was formed. The walls of the crater now shelter the bay from wind and waves creating an idyllic haven comprising a white sandy beach, a lush coral reef, and a natural sanctuary for a multitude of tropical fish. In 1970, legislature designated Hanauma Bay a protected state park.[1] All of the fish, marine animals, coral, and volcanic rock within the park boundaries are protected for public use. Hanauma Bay is favorite spot of snorkelers and scuba divers and has excellent facilities for swimming, sunbathing, and picnicking. For the past decade, Hanauma Bay has been the most popular natural attraction in Hawaii. Over 50% of the tourists in Hawaii visit Hanauma Bay. In 1991, Hanauma Bay had nearly 2 million visitors.

Due to its extreme popularity, Hanauma Bay provides a classic example of a common property resource. Pollution, crowding, and overuse has already killed off large sections of coral. The major pollutants are chemicals, nutrients, fresh water, and silt. Coral is also degraded by waders and inexperienced snorkelers who sit, stand, and walk on the reef. Most of the chemicals and nutrients are introduced into the bay by the two million visitors that arrive at the park each year. Suntan oil, picnic food, fish food[2], and septic leaks are the primary culprits. Fresh water from the outdoor showers drains into the bay and dilutes the salinity. Silt from the ocean floor is stirred up by waders. These pollutants cloud the water, disrupt coral productivity, and degrade the underwater environment.

Much of the degradation of the bay can be attributed to crowding and overuse. To reduce crowding and overuse, in 1990, the state limited the number of people that could be in the park at one time and shortened the park's visiting hours. To halt sewage leaks, park engineers shut down the on-site septic system and piped wastes out to a municipal treatment plant. To control nutrient loading, visitors have been asked not to feed the fish. By 1991, annual visitor numbers were reduced by one-third, water quality had improved, and the rate of environmental degradation had slowed. Expert opinion, however, suggests that more stringent actions will be required to halt or reverse the degradation process.

Although Hawaii has many nice beaches, sites that are comparable to Hanauma Bay were lost long ago to development and competing uses. If Hanauma Bay continues to be degraded, restoration costs are expected to very high. This research addresses environmental degradation in Hanauma Bay and develops

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[1] Hanauma Bay is officially designated a marine life conservation district and underwater beach park.

[2] Snorkeling in Hanauma Bay has been likened to swimming in an aquarium. Hand feeding the fish, for many people, is a unique and memorable experience. Popular fish foods are bread and frozen peas.

a conceptual model for managing the park for long term use. The dynamic relationships are elucidated with a phase diagram.

Theoretical Model

Coral reefs are unique and diverse ecosystems that provide the habitat and food source for a number of tropical plants, animals, and fish. Coral reefs are prized for their beauty and biological richness by skin divers, scuba divers, and marine researchers. The intricate, colored structures that we see are actually the calcium carbonate ectoskeletons of tiny marine invertebrates. These coral animals are very fragile and highly sensitive to changes in water quality, water salinity, and water temperature. Coral grows best in very clean, clear water, between 77° and 84°F.

Coral productivity is a good indicator of ecosystem health and water quality (since coral grows only in clean water). In this research, the recreational value of the bay is assumed to increase with the amount of coral in the bay and the number of visits to the bay. Visitors provide both the major source of value to the bay and the major source of environmental degradation.

In this study, the resource management problem for Hanauma Bay is characterized by two state variables and one control. The value of the bay is expressed as a function of the states: the amount of coral coverage x_{1t} (in surface area) and the number of visits to the bay x_{2t} (in visits per year), and the control u_t which limits the annual number of visitors. Letting f represent the value of the bay at time t and r the social discount rate, then the net present value of the bay is:

$$V = \int_0^T e^{-rt} f(x_{1t}, x_{2t}, u_t)\, dt \tag{1}$$

Coral productivity increases with the amount of live coral in the bay. Coral production decreases with recreational use. Therefore, the change in coral coverage over time is a function of the amount of coral coverage and the number of visitors.[3]

$$\dot{x}_{1t} = g_1(x_{1t}, x_{2t}) \tag{2}$$

Recreational demand for the bay increases with the amount of coral in the bay. Recreational demand decreases when the park becomes too crowded with visitors. The change in visitor numbers over time is function of: the amount of coral in the water, the number of visitors, and the level of control on the number of visitors.

$$\dot{x}_{2t} = g_2(x_{1t}, x_{2t}, u_t) \tag{3}$$

The objective chooses the number of visitor numbers to admit into the park in order to maximize the net value of the bay. Here, the problem is to choose u_t to maximize the present value Hamiltonian:

$$H = e^{-rt} f + \lambda_1 g_1 + \lambda_2 g_2 \tag{4}$$

Subject to the initial values of the state variables,

$$x_{1,0} = x_1^0 \qquad x_{2,0} = x_2^0 \tag{5}$$

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[3] $$\dot{x} = \frac{\partial x}{\partial t}$$

The optimality condition is[4]

$$H_u = e^{-rt} f_u + \lambda_1 g_{1_u} + \lambda_2 g_{2_u} = 0 \tag{6}$$

Equation 6 implies that at the optimum, the value gained by admitting one more person into the park will just equal the present value of future losses incurred by admitting that one last person.

The multiplier equations are[5]

$$\dot{\lambda}_i = -H_{x_i} = -(f_{x_i} + \lambda_1 g_{1_{x_i}} + \lambda_2 g_{2_{x_i}}) \qquad i = 1,2 \tag{7a-b}$$

Equation 7a implies that at the optimum, the objective function would increase by $\partial\lambda_{1t}/\partial t$ if coral grew at a rate slightly faster than g_1. Equation 7b implies that at the optimum the objective function would increase by $\partial\lambda_{2t}/\partial t$ if visitor numbers rose slightly faster than g_2.

The state equations are expressed

$$\dot{x}_i = \frac{\partial H}{\partial \lambda_i} = g_i \qquad i = 1,2 \tag{8a-b}$$

Phase Diagram Illustration

A phase diagram depicting the dynamic relationships between visitor numbers and coral production was drawn using existing general information on coral productivity and observations from Hanauma Bay. Special cases of the state equations (3) and (4) where $\dot{x}_1 = 0$ and $\dot{x}_2 = 0$ are shown in Fig. 1. The right angled arrows in Fig. 1 indicate the direction of movement. The length of the arrow indicates the rate of movement.

The curve labeled $\dot{x}_1 = 0$ represents the combinations of visitor numbers and coral coverage for which the rate of coral destruction due to recreational use just equals the rate of coral production from the living coral base. Above the curve, visitor numbers are higher, so coral is degraded more quickly than it is produced. For values in this region, $\dot{x}_1 < 0$, and the directional arrows point left (←). Below the curve, visitor numbers are lower, so coral is produced more quickly than it is degraded, and net coral growth is positive. Here, $\dot{x}_1 > 0$ and the directional arrows point to the right (→).

The curve labeled $\dot{x}_2 = 0$ represents the combinations of visitor numbers and coral coverage for which the number of visitors remains the same over time. Note by the intercept that visitor numbers will be positive when coral coverage is zero. This implies that people will continue to visit the park to enjoy the vistas, the sandy beach, and the calm waters which remain even after the coral is gone. The region at the top of the curve is flat where visitor numbers equal the physical carrying capacity of the park (x_2^{max}). For values to the left of the curve, visitor numbers will fall over time as shown by the downward directional

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[4] The abbreviated notation is defined:

$$H_u = \frac{\partial H}{\partial u}, \quad f_u = \frac{\partial f}{\partial u}, \quad g_{1_u} = \frac{\partial g_1}{\partial u}, \quad g_{2_u} = \frac{\partial g_2}{\partial u}$$

[5]

$$H_{x_i} = \frac{\partial H}{\partial x_i}, \quad f_{x_i} = \frac{\partial f}{\partial x_i}, \quad g_{1_{x_i}} = \frac{\partial g_1}{\partial x_i}, \quad g_{2_{x_i}} = \frac{\partial g_2}{\partial x_i}$$

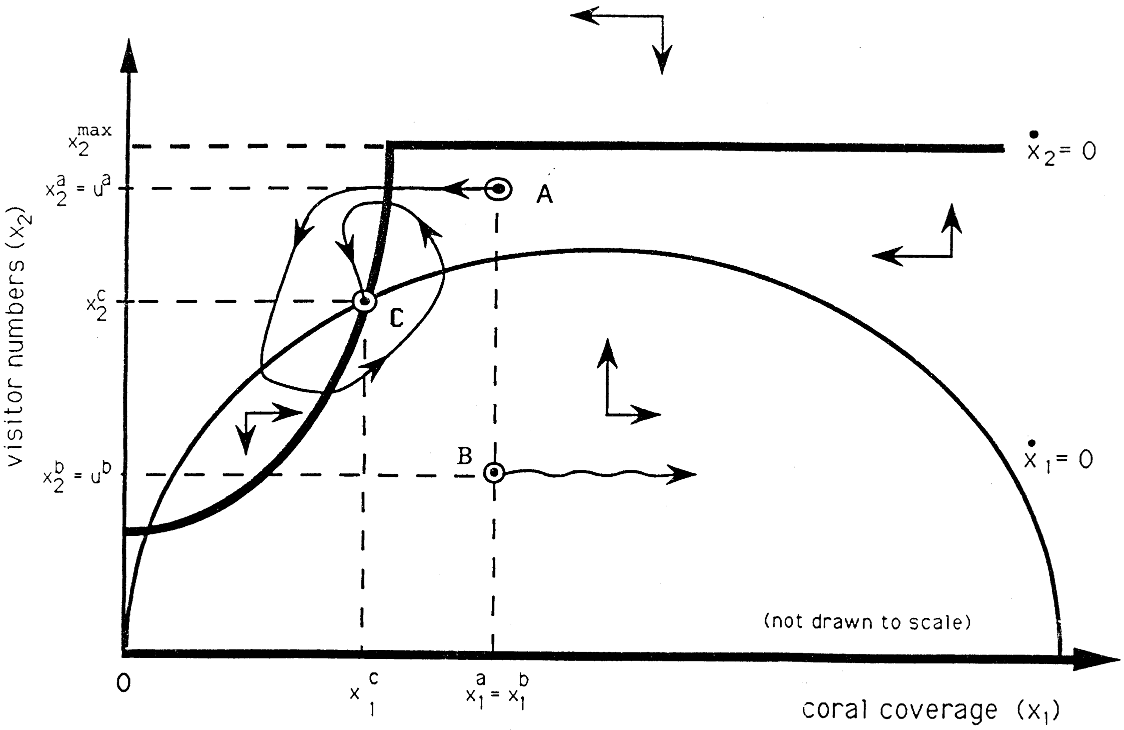

Fig. 1 Relationship between Visitor Numbers and State of the Coral Reef

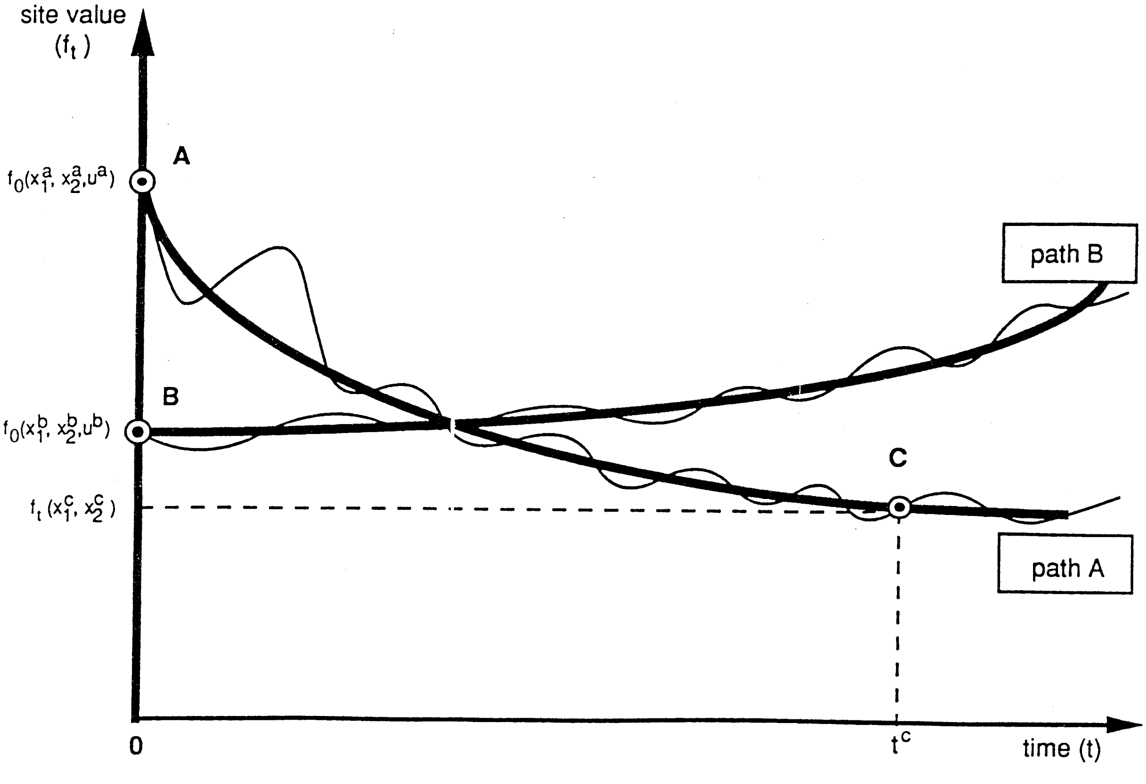

Fig. 2. Site Value over Time under Alternate Managment Strategies

arrow (↓). For values to the right of the curve, visitor numbers will increase over time, as indicated by the upward directional arrow (↑).

In Fig 1. the initial state values under the two different management strategies are shown by the points labeled A and B. Point A represents the initial state under current management practices at Hanauma Bay. Strategy A limits visitor numbers to u^a. Following the directional arrows, strategy A leads to a path that spirals downward to a stable equilibrium labeled C. Point C indicates a steady state, degraded coral environment that attracts visitors in numbers well below the park limit. The alternative strategy restricts visitor numbers to u^b. With strategy B, net coral growth is observed over time as shown by the squiggly arrow emanating from point B.

The intertemporal economic values associated with strategies A and B are mapped in Fig. 2. Note that strategy A begins at a higher level than strategy B because more people are allowed into the park under strategy A, but coral coverage is the same. Along path A, the value of the bay cycles downward as the coral becomes degraded and fewer people visit the park. The values from path B eventually surpass path A as the coral ecosystem improves. These alternate strategies can be compared by discounting and summing the area under the curves as shown in equation (1).

Diagrams of this type are useful for illustrating the costs, benefits, and risks of achieving desired environmental goals under various management practices. For example, if the environmental goal was simply to maintain the coral in its current state x_1^a, then we would choose u where $x_1 = x_1^a$ and $\dot{x}_1 = 0$. If the objective was to regenerate coral under controlled use of the park, then we would choose u where $x_1 = x_1^a$ just beneath $\dot{x}_1 = 0$.

Suggested Empirical Approach

Empirical estimates of the functional relationships will be required develop an effective park management plan. Currently, little is known about the biology of Hanauma Bay's underwater environment and its long term capacity for recreational use. Scientific investigation would certainly shed some light, but could require many years to obtain conclusive results. To protect the bay resources for current and future uses, prudence suggests initiating a management plan using existing knowledge of the ecosystem. A comprehensive management strategy should include: initial use restrictions, an ongoing data collection effort, and a control model for decision-making that can be updated as new information becomes available. For Hanauma Bay management, closed loop control with feedback is strongly indicated.

Summary

Hanauma Bay is a unique and valuable resource that is under the threat of environmental degradation from pollution, crowding, and overuse. To guide future management decisions, this work applied control theory to reveal the level of control required to maximize net values to the bay. A phase diagram was used to illustrate the dynamic relationships between the model variables and the outcomes of alternate management strategies.

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