Title
The Moorea Green Pearl Golf Course: An Assessment of the Changes and Impacts on the Coral Reef Environment from Recent Development and Land Use

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Objectives

The purpose of this study is to evaluate and describe land-use impacts of the development and maintenance of the Moorea Green Pearl Golf Resort on its surrounding coral reef lagoons. It will identify the types and degrees of change that have already taken place and predict changes that are likely to take place. It attempts to identify the causes of these changes and will attempt to reconstruct the pre-golf course baseline using available records and resources and through interviews. It includes photographic documentation of the current golf course and conditions of the surrounding areas for future use. To identify runoff inputs into the lagoon, the project included an analysis of water samples for dissolved inorganic nutrients (NO_4, $P0_4$, NO_2, and NH_4) and an analysis of sediment samples to measure the concentrations of bioavailable heavy metals on the sediment. Lastly, it will discuss future plans for the site and its contingent impacts based on this assessment.

This study refrains from addressing the approval process for the construction of the golf course.

INTRODUCTION

1. The Island

The Moorea Green Pearl Golf Resort is located in Moorea in French Polynesia.

Moorea is a small mountainous Windward island in the Society Islands (17^{o}30'S: 149^{o}50'W) that has an area of 134 km^2 and is located sixteen kilometers west of Tahiti. A barrier reef encircles the island forming a system of narrow shallow lagoons with a mean depth of 5-7 m. The reefs are intersected by 12 deep navigable passes, which are formed by offshore freshwater rivers. There are two major bays on the northern side of the island, Cook's Bay and Opunohu Bay, and several small bays around the island.

The climate is tropical with a temperature range of 27°C to 30°C during the wet season, which runs from October through April, and 24°C to 28°C during the dry season, which runs from June through September. During the humid wet season, rainstorms can be sudden, heavy, and often brief.

Although French Polynesia is an overseas entity of France, it has its own government and has considerable control over its own affairs.

1.1 Geology of Moorea

Surprisingly little is known for certain about the formation of Moorea and it remains one of the geological wonders. The island formed 1.5 to 2.5 million years ago and is now an extinct volcano (Williams, 1933, Atlas de la Polynésie Française, 1993). It is theorized that the near vertical walls of the valleys were formed by explosions from the main crater. However, a competing theory suggests that its beautiful jagged pinnacles and dramatic valleys are from a similarly tumultuous past but are instead from downfaulting and shifting and finally submergence of the volcano. Presumably, the cutting of the cliffs corresponds to the time of maximum lowering of the sea during the Pleistocene, followed by a tilting of the island to the south and less so to the east (Williams, 1933).

1.2 Formation of the Barrier Reef

The barrier coral reef system did not form until after the island finished shifting and natural erosion had halted (Marshall, 1913). The development of coral reef was delayed by the detritus carried down from the valleys (Marshall, 1913).   The great submergence of the island is believed to have been essential in allowing reef upgrowth by removing all coastal detritus and depositing it at great depths.

The rivers in Moorea carry very little detritus, and there was virtually no natural erosion until human development began on the island. The advent of sedimentation from land-use alters the conditions under which the reefs could form. It is a possibility that this new influx of detritus could prevent the growth of new coral, reduce its ability to recover, or even reduce existing coral.

2. The Golf Resort

The Moorea Green Pearl Golf Resort (Fig. 1) was a project designed by Nicklaus Design, founded by golf legend Jack Nicklaus. The company has developed over 300 golf courses worldwide. These courses have hosted nearly 600 professional tournaments. Construction of the 18-hole championship Moorea Green Pearl Golf Resort began in 2005 and opened its first nine holes in April of 2007. The remaining nine holes were open for play in January of 2008.

Fig. 1. Photographs of the Moorea Green Pearl Golf Course: (a) fairway, (b) clubhouse and putting green, (c) view of grounds from hillside, (d) lagoon edge of property.

The golf course is located in the Temae region in the northeast area of the island (Fig. 2). The golf course dominates the Temae region, reaching from the lagoon to and partially up the mountainside. The current area of the golf course is 165 hectares, but the total area of the final resort will likely increase with the construction of the hotel and residential villas.

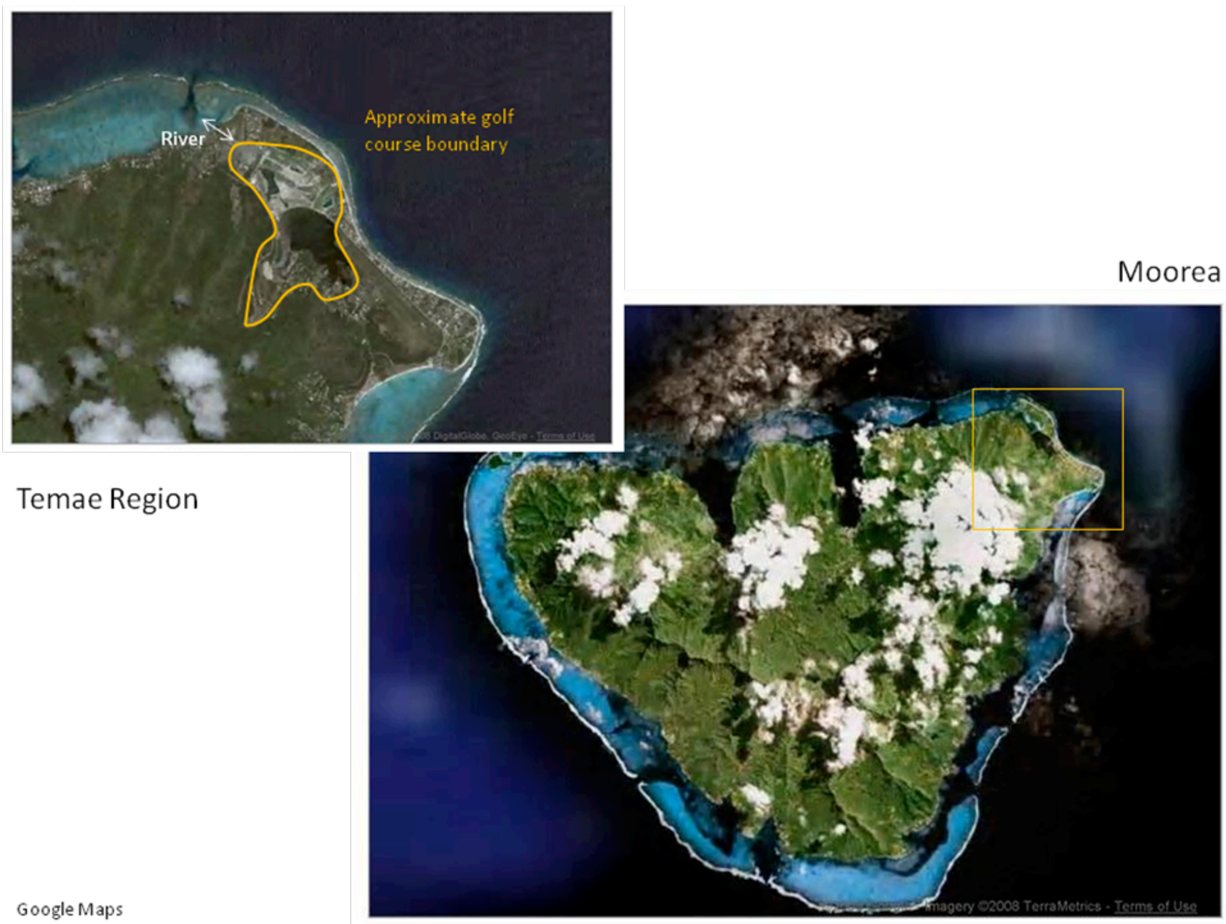


Fig. 2. Satellite Images of Moorea and Temae Region. Approximate boundary of golf course (upper left).

2.1 Construction of the Golf Course

Development of the Moorea Green Pearl Golf Course included filling in the wetland that connected Lake Temae to the lagoon by way of a small river (fig. 2). Wetlands are rare in French Polynesia and are usually very small (Fontaine, 1993). They can serve as an ecologically beneficial pollution filter, but otherwise very little is known about them. Much of the former wetland habitat has been lost to extensive coastal development on some of the Polynesian islands. Some endemic species of birds have suffered a serious decline in population due to habitat loss, including the Little Heron (*Butorides striatus*) and the Pacific Black Duck (*Anas Superciliosa)*(Fontaine, 1993).

3. Marine Protected Areas around Moorea

A series of eight Marine Protected Areas (MPAs) was established in the lagoon around Moorea from 1998 to 2001 (fig. 3, shown in red). The sites chosen were primarily determined by concerns of overfishing, although land-based pollution is largely responsible for the degradation of the marine habitats.

The process of establishing the MPAs added to the conflicts between lagoon stakeholders (Walker, 2002) (including all non-commercial, commercial, non-extractive, extractive, non-economic, and economic uses, e.g., divers, fishers, hotels, and lagoon tour operators etc.). The scarcity of fish from overfishing and high costs of living increased tensions amongst fisherman. Hotels, which often have over-water bungalows, and lagoon tour operators, who offer activities such as shark and ray feeding or scuba diving, also disagreed on zoning parameters. With each group feeling as though they were being dismissed by the government, and also because of competition for zoning interests, the tensions that already existed amongst the community were further exacerbated (Walker, 2002).

The government maps were presented to be scientific and official because they were developed using computer technologies and GIS (Edlund and Knupp, 2001). However, the models were flawed and were missing many important variables by not taking into account some economic values, such as areas that are visited by tourists, or the ecological value of an area. Some of the politics behind the decision-making process were questioned by the community because of the lack of scientific basis behind the designation of the MPAs (Walker, 2002).

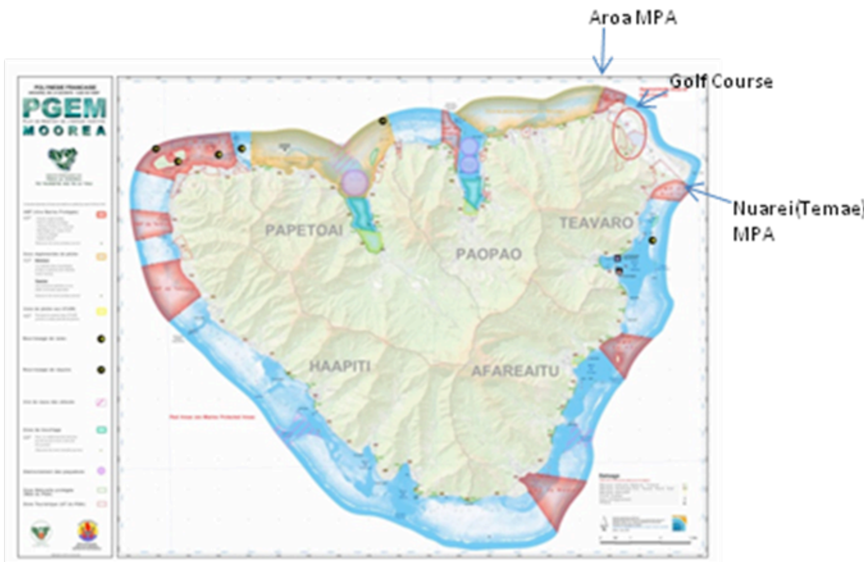


Fig. 3. Map of Marine Protected Areas in Moorea, established by the PGEM (Plan de Gestion de l'Espace Maritime). Marine Protected Areas are indicated by red shaded areas.

The local community was frustrated and angry for not being included in the decision-making process and felt resentful for not having access to the GIS and other privileged information. The local controversy behind the MPAs is unfortunate, as MPAs have been shown to be effective in many places (Lison de Loma et al., 2008). Coral reefs in Moorea are in need of protection and benefit from these areas (Wilkinson, 1999).

Curiously, the golf course was approved to be built near two Marine Protected Areas (Fig. 3), the Aroa Marine Protected Area to the north, and the Nuarei (Temae Beach) Marine Protected Area to the south-east. In fact, the river that flows directly from the golf course empties into the Aroa Marine Protected Area.

4. Coral in Moorea

Moorea has all major coral reef types along its 60 km of coast, including fringing reef, back reef, fore reef, barrier reef, and lagoon patch reefs. The reefs are considered to be in good condition, but they have recently faced various risks posed to them.

The coral reef environment is the fastest disappearing ecosystem in the world, but the diversity in Moorea is still considered to be good (MCR LTER). Coral species in Moorea lagoons include *Porcillopora eydouxi, Porcillopora meandrina, Porites rus, Millepora* spp.*, Porites lobata, Montastrea curta, Fungia* spp.*, Porillopora verrucosa, Montipora* spp.*, Acropora pulcra, and Acropora hyacithus.*

4.1 Natural Threats To Coral

Natural threats to coral are often weather related, such as cyclones or sea surface temperature and salinity changes from weather patterns such as El Niños, as well from as desiccation during extreme low tides (Glynn, 1990). There have been several outbreaks of the crown-of-thorns starfish (*Acanthaster planci)* since the 1970s that graze on coral polyps mostly at night and can devastate large areas of coral in its path. (Porter, 1972; Done, 1985; Adjeroud et al., 2002) It is one of the greatest contributors to loss of coral reefs. The coral in Moorea have been subjected to predation by *A. planci* in the past (Done et al., 1991) as well as presently. The cause of sudden outbreaks of *A. planci* is not understood, although it is believed to be linked to agricultural runoff which causes algal blooms. Coral polyps that usually feed on the eggs of *A. planci* are instead supplied with large amounts of food from the algae. There is also evidence that overfishing the fish that are predators of *A. planci* has contributed to increased numbers of the starfish (Done et al., 1991; Barnes and Hughes, 1999).

4.2 Anthropogenic Threats to Coral

Anthropogenic threats to coral include pollution, overfishing and destructive fishing practices (UVI, 2001, Knowlton, 2008). Tourism may also play a part through careless diving or for collectables. Land-based runoff is most likely the most significant threat to coral. Runoff is caused by coastal development, agriculture, erosion from deforestation, and dredging (Bastidas and Garcia, 1999; Esslomont et al., 2000, Fallon et al., 2002). Construction of the golf course included all four of these. Sediment, pesticides, nutrients, fuel, and heavy metals may enter the lagoons through runoff (Guzman, 1992).

CAPSTONE PROJECT OVERVIEW

The four components of the capstone project were designed to create a comprehensive overview of the golf resort project and its ecological consequences. The project includes 1.) A photographic documentary of the existing golf course, 2.) Measurements of heavy metals and nutrients in the lagoon, 3.) A reconstruction of the pre-golf course through informal, anonymous interviews with residents of Moorea and referencing available literature and resources, and 4.) Research into future developments of the Moorea Green Pearl Golf Resort, and a prognosis of its environmental consequences.

Although some environmental groups have focused on the South Pacific (e.g., Reef Check in Bora Bora and Conservation International in Samoa), the progress of the golf course has not been followed by any conservation groups.

5. Photographic Documentation

Comprehensive photographic documentation was assembled by exploring the entire grounds of the golf course and surrounding areas on foot over several days. An effort was made to capture every angle of the golf course and represent completed developments as well as works in progress. The first eight photographs were taken in March and April of 2008 (Figs. 5 and 6) and represent some of the works in progress. Figure 4 is a map of the photographing sites. Please see the Appendix for additional photographs of the development and of areas of the golf course that are open for play.

Fig. 4. Map of where photographs were taken.

Fig. 5. (a) Future site of hotel, (b) wetland fill, (c) loose sediment, and (d) refuse along lake edge.

Figure 5 are photographs of the Moorea Green Pearl golf course taken in late March of 2008. Current developments shown here include the future site of the hotel (fig. 5a) and continued filling in of the wetland (fig. 5b). The future plans of the wetland-fill were unclear to me from this study. There were many large piles of loose sediment throughout the golf resort project site (fig. 5c), and refuse now litters the edge of the remaining wetland (fig. 5d).

More photographs from March of 2008 are shown in Figure 6. There are algal blooms in the runoff along the golf course (fig. 6a), and additional piles of loose sediment (fig. 6b). Figure 6c shows part of the future site of the hotel. Figure 6d shows golf course property that has not been landscaped.

Fig. 6. Algal growth (a), loose sediment (b), development of small artificial lake and future site of hotel (c). golf property that has not been landscaped (d).

Fig. 7. Beginning stages of golf course development. Terracing (a), future golf ponds (b), draining, filling, and reshaping of Lake Temae and wetland(c) and (d), filling of “new” lake (e), and coastal development (f). 2005-2006 Source: Moorea Golf Resort website (http://www.moorea-resort.com)

Figure 7a shows the destructive method of terracing. Terracing causes substantial amount of erosion. These pictures were from during the early stages of developing the golf course in 2005. Figure 7b will be a pond on the golf course. Figures 7c, 7d, and 7e show development of the “new” lake, which was a major overhaul of the original natural lake. Figure 7f shows development of the golf course alongside the lagoon.

5.1 Water Usage

The irrigation system for the golf course is not designed efficiently (Fig. 8). High volume sprinklers were observed both day and night. The water is projected high into the air and a high volume of water was observed to land on the pavement. More efficient golf irrigation options include micro irrigation (drip, trickle, or spray)(Dorota et al., 2003). Efficient practices include irrigating at night or early morning (the golf course had its sprinklers on at midday (Fig. 8, right panel)), and taking precipitation into consideration for the watering schedule. There is a dry season in Moorea, but these photographs were taken during the tail end of the wet season. Moorea’s average annual rainfall is 1800mm (109 inches) (MCR LTER). According to interviews with local residents, the greens are watered on a daily basis.

Excessive irrigation contributes to the runoff into the lake and subsequently to the lagoon. It also has the potential to enter the groundwater and affect the salinity in the near-shore aquifer as the entire Temae region is underlain by a very porous layer of limestone (Burlot et al., 1985). Additionally, the amount of water used in maintaining the greens can also overtax the island’s limited water supply (Falkland,1992; UNESCO).

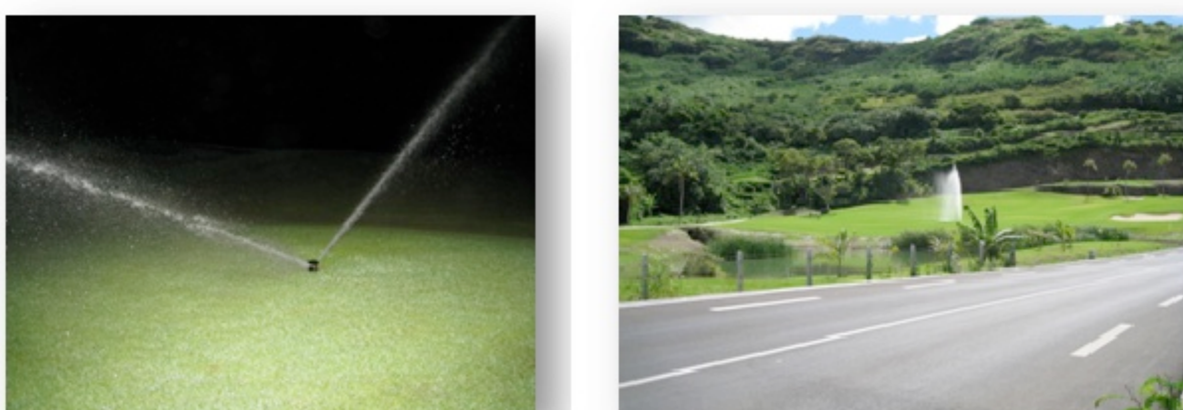


Fig. 8. Irrigation of the greens night and day using high volume sprinklers.

5.2 Sedimentation

Moorea's geology coupled with its high precipitation creates a potential for sedimentation caused by development (Takara et al., 2002). Exposed soil and materials can be transported via runoff and be deposited onto the near-shore coral reefs.

Sedimentation can be a serious threat to the resilience of coral in several ways:

- Creating turbid water that reduces the amount of light that can reach symbiotic zooxanthellae for photosynthesis (Bryant et al., 1998)
- Restrict suitable areas for larval settlement
- Physically smother coral polyps or bury colonies
- Inhibit reproduction
- Obstruct feeding
- Reduce growth rate
- Limit ability to recover
- Provide substrate for algal growth (Rogers, 1990, Schleyer, 2003)

Sediment can also serve as a vehicle for pollutants loaded on its particle surfaces.

5.3 Resilience to sedimentation

Some coral are able to shed sediment particles through a variety of mechanisms (Schleyer, 2003), but it is energetically expensive and eventually they reach a point where they can no longer do this and they die (Riegl and Branch, 1995). Recently a study in Moorea showed a symbiotic relationship between *Acropora* and *Pocillipora* and a tiny trapeziid crab that sweeps sediment from the coral in exchange for a home, which helps to mitigate the effects of sedimentation on coral to a degree (Stewart and Holbrook, 2006). A loss of these crabs would lower the survival rate of coral subjected to sedimentation. In the study, 50% to 80% more coral survived if it housed crabs. Coral that lacked crabs suffered more bleaching, slower growth and had higher sediment load (Stewart and Holbrook, 2006). The importance of the crab for coral survivability stresses the importance of a single ecological role, and the need to prevent the alteration of its habitat.

Careless land-use methods and increased development have raised the amount of sediment load on coral (Dikou and Woesik, 2006). Development increases the amount of water runoff of exposed soils, and sediments from roads, terracing, agriculture, and deforestation and can easily exceed the small load that is manageable on coral (Ryan et al., 2008).

6. Sample Sites

Five sites were chosen for sampling of nutrients and trace metals (map, fig. 9)(GPS, table 1). The sites were selected to look for patterns or evidence of runoff based on distance from the golf course. The first site was Lake Temae, around which the golf course is built. The next sample site was at the river mouth, which was how Lake Temae flowed into the lagoon through the wetland. There is now wetland fill, but also evidence of runoff from the golf course into the river. Aroa Point was the next site, and is located in the lagoon closest to the golf course and river mouth. Temae Beach was selected because it is still in the Temae region but further than Aroa Point. Furthermore, there is no direct path for runoff to flow from the golf course to Temae Beach, but there is an extensive aquifer that runs through the porous limestone layer beneath the Temae region, making it an interesting site to look at. The last site, Motu Tiahura was selected as a control. It is more distant from the golf course, but also a Marine Protected Area like Aroa and Temae Beach. Furthermore, all three sites were similar in that 50m offshore the depths were 2-3m, and both coral density and diversity were similar. Motu Tiahura was originally selected because there were the least rivers in that part of the island. However, it did not turn out to be a good control site. I later learned that the region has high nutrient runoff, although I have not yet confirmed the source.

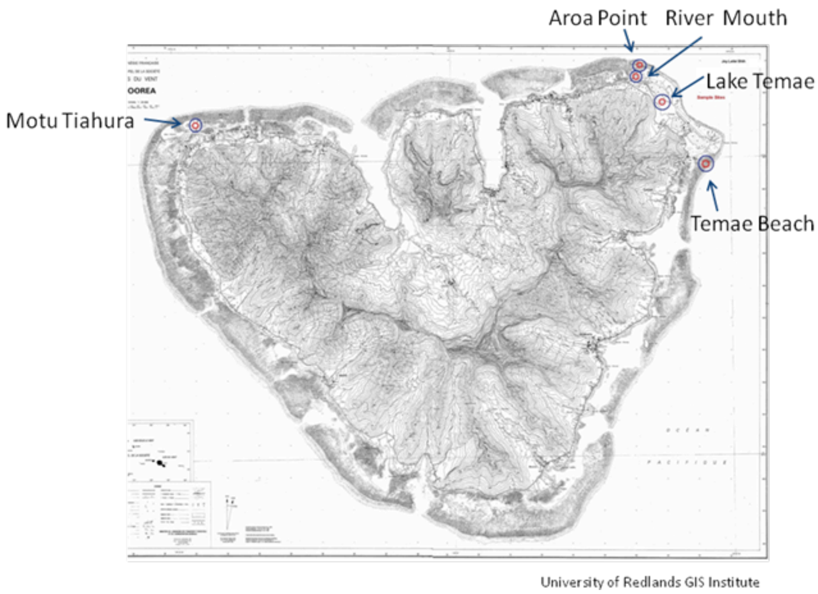


Fig. 9. Map showing location of sampling sites.

Sampling Site	GPS Coordinates
Temae Beach 1	S 17° 29.943', W 148° 45.493'
Temae Beach 2	S 17° 29.984', W 149° 45.576'
Aroa Point	S 17° 28.430', W 149° 46.777'
Lake Temae	S 17° 28.977', W 149° 46.268'
Rivermouth	S 17°28.555', W 149° 46.686'
Motu Tiahura	S 17° 29.204', W 149° 54.533'

Table 1. GPS location of sampling sites.

7. Metals

Metals entering the environment come from various sources, including development, sewage discharges and topsoil erosion. Metals can also leach from materials, such as fuel or batteries. Metals are also used in agriculture as fungicides or pesticides and can contaminate the marine environment through runoff. The toxicity of heavy metals to some marine environments has been determined in a multitude of studies (Bat et al., 1998, Deheyn et al., 2004).

7.1 Methods

Sediment samples were collected at each site 3 or 4 times, over a period of 16 days from 24 March, 2008 to 8 April, 2008. The sediments from the lagoons were from a depth of 2 to 3m, and the sediment samples of Lake Temae and the river mouth were from depth of 0.5 to 1m. The sediment samples were stored in 10% HCl acid-washed centrifuge tubes and were kept frozen at -20°C.

Trace heavy metal concentrations were measured using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) at the Scripps Institution of Oceanography analytical facilities.

To prepare for the analysis, the samples were first defrosted and dried in the oven. The samples were then weighed (0.1g) and microwave digested in 500 µl of HNO_3 45%, and then diluted with 5 ml of MilliQ water. After allowing any remaining particles to settle, the supernatant was diluted (0.4 ml sample = 3.6 ml MilliQ water) and placed into ICP tubes and put into the ICP. Blanks control were used in the analysis. Duplicate measurements were made for each of the 33 samples in the analysis.

7.2 Results

Heavy metals that were detected in the ICP-OES analysis were Al, As, Cr, Cu, Fe, Mn, Ni, Pb, Sr, Ti, and V (fig. 10).

A clear trend was observed in several of these metals, in particular, Al, Ni, Pb, Cu, Mn, and Ti, with the highest concentrations (in mg/g) occurring at the lake, and diminishing with distance from the golf course (fig 11.)

Figure 11 is plotted along the horizontal axis for each metal. Each site is indicated by color and arranged to show distance from the golf course going from left to right, that is, Lake Temae (dark blue), the river mouth (red), Aroa Point (green), Temae Beach (purple), and Motu Tiahura (light blue).

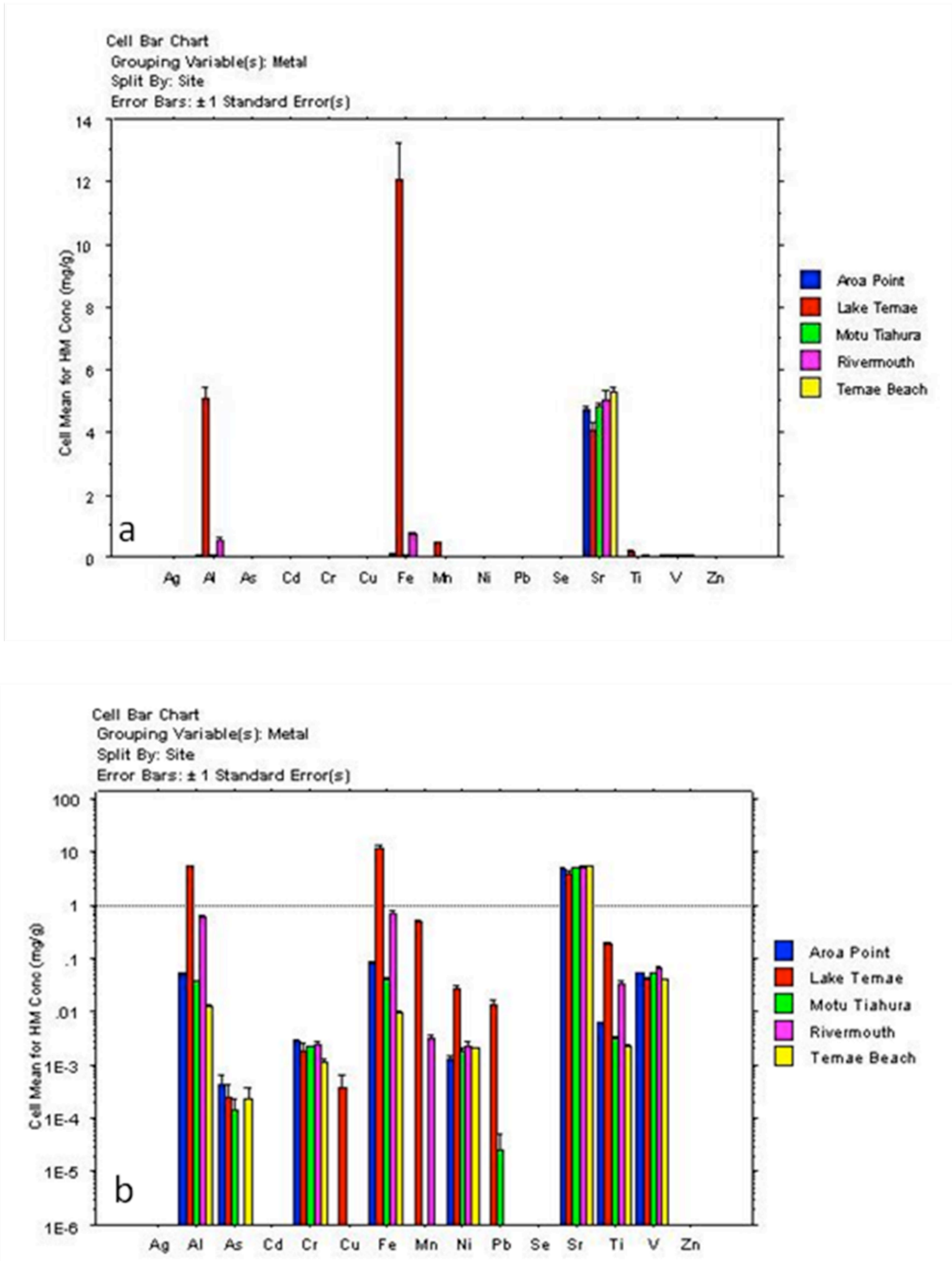


Fig. 10. ICP-OES results for all measured metals. (a) Mean heavy metal Concentration (mg/g), (b) on logarithmic scale. Standard deviations are shown.

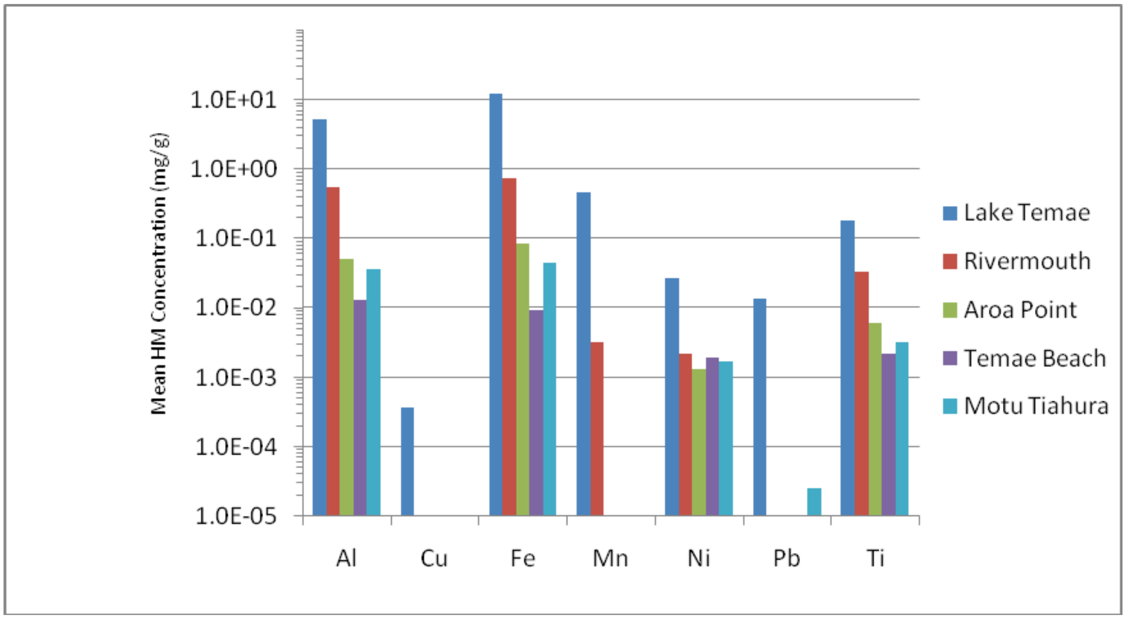


Fig. 11. Average concentration (mg/g) on logarithmic scale (y-axis) for each metal. Arranged to show concentrations of each metal in relation to distance to golf course, from left to right, i.e., Lake Temae (dark blue), the river mouth (red), Aroa Point (green), Temae Beach (purple), and Motu Tiahura (light blue).

Average concentration(mg/g) of each metal by site are listed in Table 2.

	Al		Cu		Fe		Mn		Ni		Pb		Ti		Sr	
Lake Temae	5.103	±1.316	3.70E-04	±0.001	12.086	±0.003	0.457	±0.116	0.027	±0.012	1.38E-02	±0.008	0.178	±0.095	4.070	±0.506
Rivermouth	0.552	±0.249	1.00E-06	±2.221E-22	0.725	±4.577	0.003	±0.003	0.002	±0.001	1.00E-06	±2.212E-22	0.033	±0.0199	5.036	±0.809
Aroa Point	0.051	±0.015	1.00E-06	±2.212E-22	0.084	±0.362	0.000	±2.204E-22	0.001	±0.001	1.00E-06	±2.204E-22	0.006	±0.001	4.714	±0.961
Temae Beach	0.013	±0.003	1.00E-06	±2.212E-22	0.009	±0.009	0.000	±2.221E-22	0.002	±0.0003	1.00E-06	±2.221E-22	0.002	±0.0004	5.244	±0.399
Motu Tiahura	0.036	±0.004	1.00E-06	±2.204E-22	0.045	±0.011	0.000	±2.2122E-22	0.002	±0.001	2.50E-05	±0.0001	0.003	±0.001	4.841	±0.443

Table 2. Average concentration (mg/g)±SD for each metal by site.

7.3 Discussion

Baseline levels of metals with which to compare these levels to were not found in the literature. There have not been measurements of trace heavy metals in the Temae region to look at the effects of the golf course project. Geologic references suggest that lead, copper, manganese, nickel, strontium and titanium do not naturally occur on the island in significant amounts. Some aluminum and iron are thought to occur naturally.

The ICP results suggest that heavy metals are entering the marine environment from the golf course.

Some of the possible sources include: Manganese and copper present in fungicides, nickel from batteries, lead from fuel, paints, or batteries, titanium from paint and cement, and any combination of metals from materials used in development of the golf course. Strontium is often indicative of land erosion

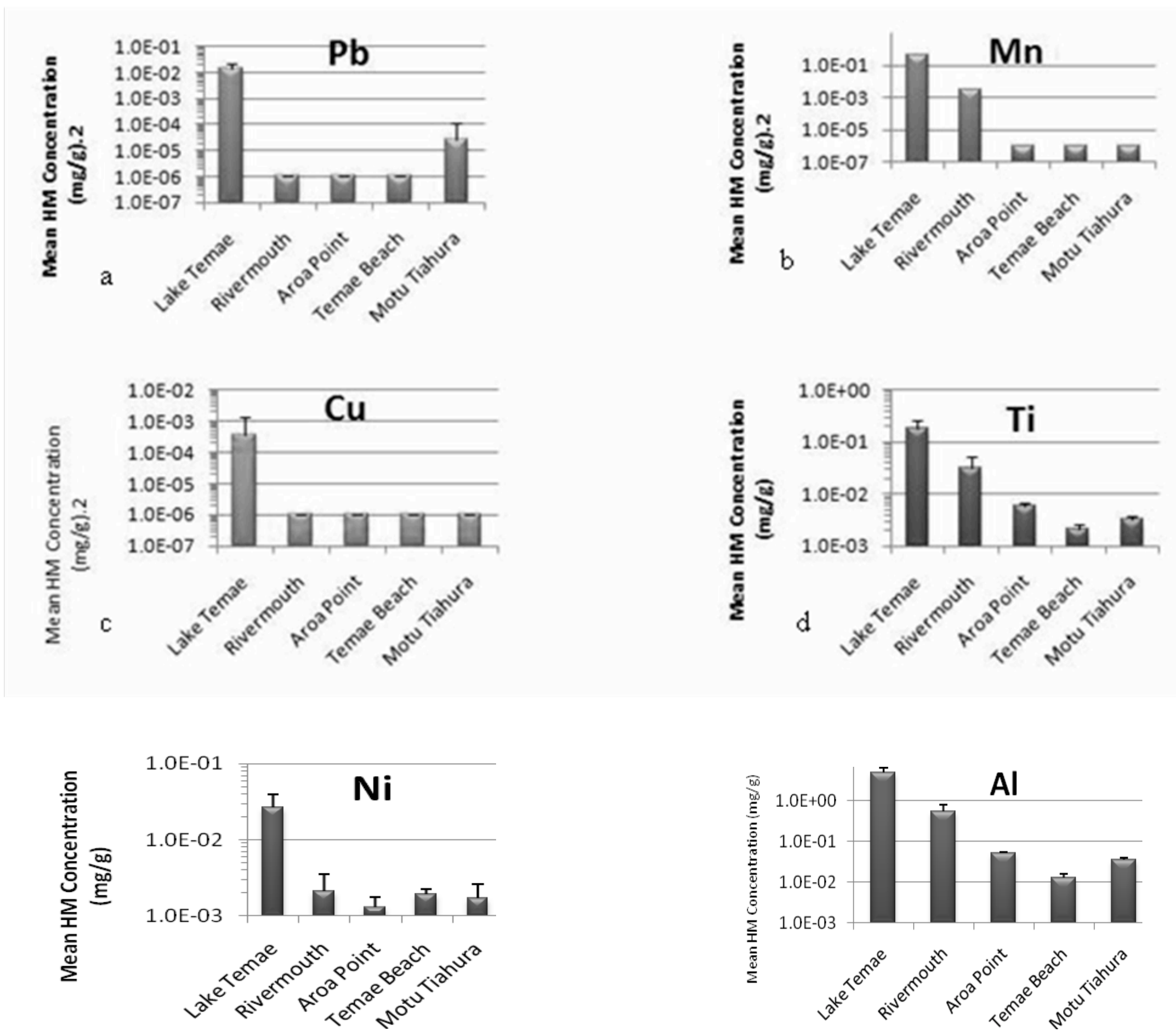


Fig. 12. Mean concentration (mg/g) of individual metals by distance from golf course, from left to right. Pb (a), Mn (b), Cu (c), Ti (d), Ni (e), and Al (f) with standard deviation.

Metals were graphed individually to show metals by site (fig. 12). The sampling sites are listed along the horizontal axis, ordered by distance from the golf course from left to right. Noteworthy concentrations of Pb (0.013838mg/g) and Cu (0.00037mg) were found only at Lake Temae (the golf course), with the exception of a lower amount of Pb at Motu Tiahura (0.000025mg/g). For all other sites Cu and Pb were virtually undetectable (1E 10^{-6} mg/g).

Mn, Ti, Ni, and Al all showed levels declining with distance from the golf course, with a slight rise at Motu Tiahura, though still having one of the lowest concentrations. Mn had a high of 0.4569 mg/g at Lake Temae and 0.003258 at the river mouth. All other sites were at (1E 10^{-6} mg/g). For Al, Lake Temae had the highest concentration at 5.103223 mg/g, followed by the river mouth at 0.551783. The other three sites had concentrations of 0.05 mg/g or below. Please see all values in Table 2. Ti showed a similar trend, with Lake Temae with the highest levels at 0.178337 mg/g, followed by the river mouth at 0.03273 mg/g at the river mouth, 0.006067 mg/g at Aroa Point, and 0.002176mg/g and 0.003242mg/g at Temae Beach and Motu Tiahura respectively. Nickel was correspondingly high at Lake Temae at a concentration of 0.026802 mg/g. All other sites were much lower, all at or a little below 0.002 mg/g.

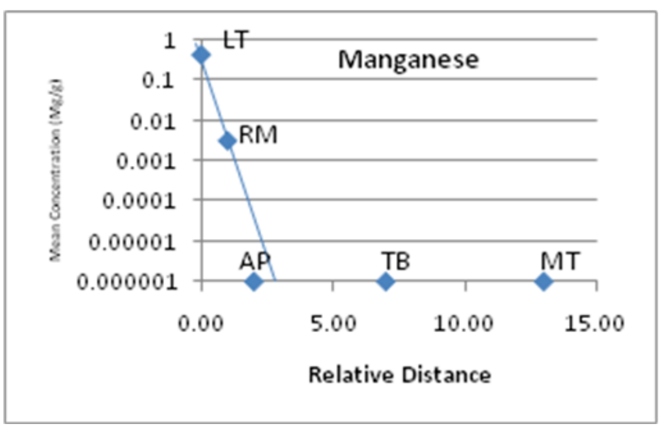


Fig. 13. Mean concentration (mg/g) of Manganese by relative distance to golf course with LakeTemae=0. LT=Lake Temae, RM=river mouth, AP=Aroa Point, TB=Temae Beach, MT=Motu Tiahura.

Figure 13 is plotted to show the decline of Mn concentrations with distance from the golf course. Distance is represented by relative distance, that is, Lake Temae is set at 0, the river mouth is at a distance of 1, Aroa Point is at a relative distance of 2, or twice as far from the golf course as the river mouth, Temae Beach at 7, and Motu Tiahura at 13.

7.4 Toxicity of Heavy Metals

Copper has been shown to impair coral fertilization (Reichelt-Brushett and Mickalek-Wagner, 2005; Victor and Richmond, 2005). In other marine life it can cause damage to gills, liver kidneys, and the nervous system. It also interferes with sensory mechanisms (Belanger et al., 2006). Lead is known to be a neurotoxin. Nickel has also been shown to be toxic to marine life. How heavy metals affect some organism is not clear, but it is suggested that they may block enzyme systems of interfere with metabolites (Madoni, 1999)

8. Nutrients

Corals have evolved in the lowest nutrient marine environment and yet are one of the most productive and diverse ecosystems in the world (Pauley, 1997). While nutrients are essential for growth of all life forms, healthy reefs are able to maintain high productivity by recycling very small amounts of nutrients in the water (Szmant-Froelich, 1983). Typically, tropical surface waters contain nearly undetectable levels of nutrients. Nitrogen and phosphorus are abundant in the deep sea, but the cold nutrient-rich water does not mix with warmer surface layers because of stratification (Dubinsky, 1990).

Even a tiny excess of nutrients can cause a phase shift from coral to algal dominance on the reef (Banner, 1974, Meng et al., 2008). Eutrophication lowers the amount of dissolved O_2 in the seawater and can affect other reef life as well as lower water quality and visibility (McClanahan et al., 2007). Switching back to a coral-dominated state is comparably difficult and any recovery is slow (Bell, 1992).

8.1 Methods

To get nutrient levels, seawater was sampled from each site either 3 or 4 times over a period of 16 days from 24 March, 2008 to 8 April, 2008. The seawater was taken from a depth of 1m and was filtered through a 0.45μm syringe filter. The samples were then frozen at -20°C until they were brought back to Scripps Institution of Oceanography for analysis. The samples were analyzed for dissolved inorganic nutrients at the Oceanographic Data Facilities at Scripps Institution of Oceanography.

8.2 Results

The data (table 3) show similar levels to nutrient samples collected for the Moorea Coral Reef LTER. I expected to see higher concentrations of nutrients closer to the golf course from the usage of nitrogen and phosphorous fertilizers, however, there was no clear trend. Aroa Point had the highest levels for NO_3 (0.43μM), PO_4 (0.22μM), and NH (1.69μM)$_4$. Lake Temae and the Rivermouth also had high levels of NH_4 (1.18 and1.4μM, respectively), but surprisingly Lake Temae had the lowest levels of PO_4 (0.07μM). Motu Tiahura also had high levels of NH_4 (1.04μM). Temae Beach has the lowest concentrations for all nutrients, and NO2 was fairly equal across all sites. There was a pulse of NO_3 that occurred around April 4 at Lake Temae, Aroa Point, Temae Beach and Motu Tiahura, and of NH_4 at Lake Temae and Temae Beach which would most likely be from land-based runoff due to precipitation (see table 3.)

Most of these values fall within the typical range. Nutrients levels in the offshore reef area are usually between 0.1 to 0.5 μM in nitrogen compounds, and 0.01 to 0.05 μM for phosphates. Levels in the lagoons typically range from 0.5 to 2.0 μM for nitrogen compounds and 0.1 to0.5 μM for phosphates.

Nutrient Concentrations in umol/L (uM)

Sample No.	ID Number	NO3	PO4	SIL	NO2	NH4
1	TB3-24-1	0.16	0.2	1.1	0.02	0.03
2	TB3-24-2	0.17	0.19	1.1	0.02	0.01
3	TB3-27-1	0.36	0.24	1.1	0.04	0.2
4	TB3-27-2	0.37	0.23	1.0	0.04	0.17
5	TB4-4	0.48	0.23	**109.3**	0.04	1.1 *
6	AP3-28	0.43	0.24	1.4	0.05	0.18
7	AP4-4	0.64	0.24	**136.8**	0.05	1.2 *
8	AP4-6	0.38	0.15	1.1	0.02	2.61
9	AP4-8	0.28	0.23	**120.5**	0.03	2.35 *
10	LT4-4	0.54	0.25	**215.6**	0.08	2.62 *
11	LT4-5	0.27	0.04	**215.6**	0.01	1.26 *
12	LT4-7	0.18	0	**215.6**	0.01	0.41 *
13	LT4-8	0.09	0	**215.6**	0.00	0.44 *
14	RM4-4	0.25	0.08	**82.6**	0.00	1.62 *
15	RM4-6	0.24	0.2	**101.5**	0.03	1.9 *
16	RM4-8	0.24	0.17	**132.6**	0.04	0.67 *
17	MT4-5	0.64	0.22	**169.1**	0.05	1.1 *
18	MT4-7	0.32	0.16	**84.9**	0.02	1.79 *
19	MT4-8	0.35	0.23	**102.9**	0.05	0.33 *

*** [SiO3] values no good due to Si contamination from glass vials they were stored in**

Table 3. Locations are abbreviated, followed by the sampling date. TB=Temae Beach, AP=Aroa Point, LT=Lake Temae, RM=river mouth, MT=Motu Tiahura.

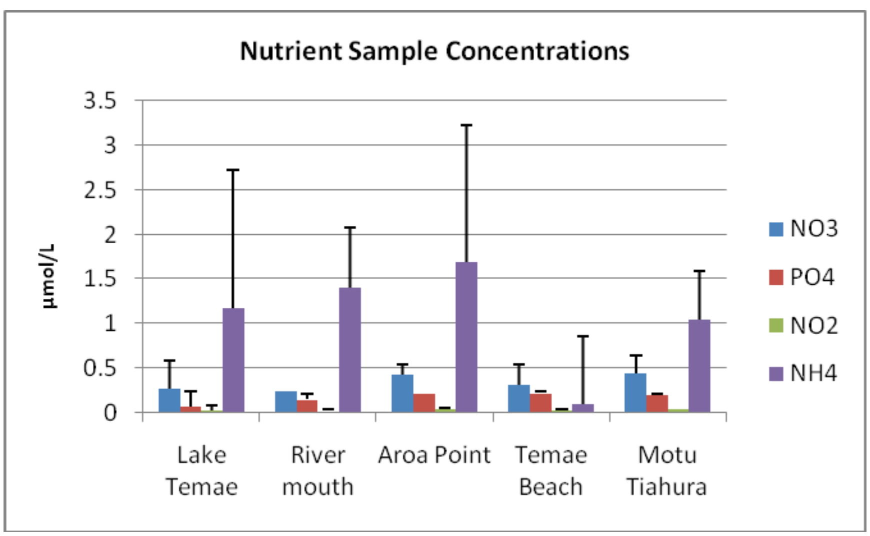


Fig. 14. Mean nutrient concentrations by site with standard deviation. Sites are plotted in order to show distance from golf course from left to right.

Average nutrient concentrations were graphed (Fig. 14) by site. Sampling sites are plotted on the x-axis from left to right moving away from the golf course, that is, Lake Temae (golf course), followed by the rivermouth, then Aroa Point off the river mouth, and then the two lagoon sites each further from the golf course. Lake Temae, the river mouth, and Aroa Point show higher levels of NH4, which could be from fertilizer application on the golf course.

8.3 Discussion

The major source of nutrient pulses in the lagoon are from land and runoff that occur with precipitation (Lapointe, 1996), and thus a possibility exists that it can also occur from excessive irrigation. This is important for the golf course because of the observed irrigation practices, the nitrogen and phosphorous fertilizers that are applied, and because of its proximity to the lagoon. The nutrients applied to the golf course can easily increase the amount of nutrients entering the lagoon.

9. Pesticides

The study of current pesticide usage on the golf course was mostly outside the scope of this project, but a few comments can be made. Golf courses in general have high pesticide usage and are notorious for cases of pesticide poisoning in employees and players, as well as in wildlife that live near the grounds (Cox, 1991). The sport demands flawless greens, manicured grounds, and strong turf. The discerning patron expects a certain image and setting that includes plants that do not normally exist in the region. They are often from very different habitats and must be coaxed to grow well in a very different environment, especially in a climate like that of Moorea. Pesticides can enter rivers and groundwater and be delivered to coral reefs.

In the pre-assessment study done in 2005, several types of pesticides were observed on the grounds (Boutillier and Duane, 2006). They noted any bags that were lying on the property. These included:

- Chlorpyrifos: impairs nervous system function, highly toxic to fish, benthic community, and estuarine organisms
- Atrazine : highly toxic to aquatic plants, endocrine disrupter
- Benfluralin: decreases red blood cell count, toxic to fish, phytoplankton, and mollusks
- Dicamba-: toxic to fetus, can affect the central nervous system

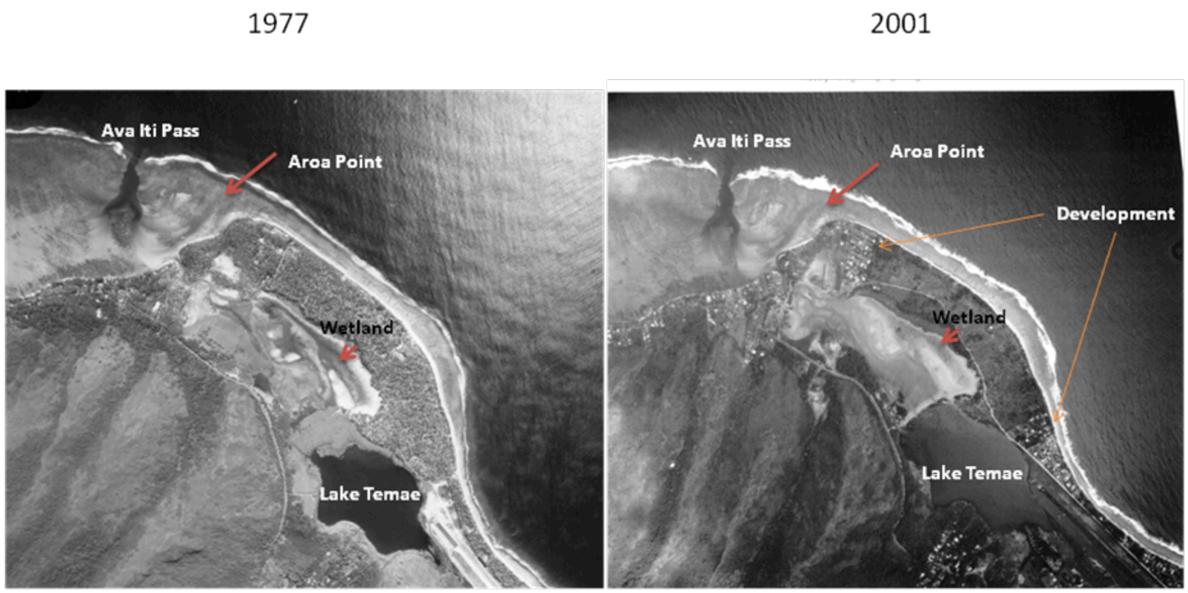
- Thiophanate-methyl: causes hyperthyroidism, decreases sperm formation
- Diquat: causes cataracts, can inhibit growth, some toxicity to fish, mollusks and crustaceans
- Pendimethalin: toxic to liver, extremely toxic to fish and invertebrates
- Disulfoton: Causes optic nerve degeneration, harmful to zooplankton (PAN pesticides database; U.S. EPA; PMEP)

This study attempted to duplicate their findings but was not successful, and inquiries to Nicklaus Design about current usage did not produce any response. However, it is likely that the golf course continues to use at least some of the same pesticides, fungicides, and herbicides that it did in 2005.

There is good possibility that this championship Nicklaus golf course will one day host professional tournaments. This could put incredible strain on the local ecosystem, not just from the event itself, but also from the treatment of the grounds before tournaments. It is common practice to apply large amounts of chemicals and fertilizers to ensure that the greens are attractive and strong before a tournament (Metcalfe et al., 2007). Again, the proximity of the golf course to the lagoon offers virtually no buffer between the grounds and the lagoon and coral. High precipitation and runoff can quickly deliver those pesticides to near shore reefs (Kitada, 2008).

10. Large Scale Visible Changes

The Department of Urbanism (Service de l'Urbanisme), was able to provide a series of aerial photographs of the Temae region taken from 1977 through 2006. The photographs offer a fantastic overview of the area now occupied by the golf course.



Service de l'Urbanisme, Polynésie Française

Fig. 15. Aerial photos of the Temae region in 1977 (left) and 2001 (right).

These aerial photographs of the Temae region were taken over two decades apart (fig. 15, 1977 (left) and 2001 (right)). Some clearing and development have occurred along the north and east coasts of the region but the lake-wetland-lagoon and pass system has remained intact and has maintained a similar morphological structure. The northern portion of the lake that is the wetland fills and retreats with the tide. This natural cycle gave the opportunity for small fish to swim upstream with the tide, and Green crabs to emerge during the low tide. The Green crabs were a local food source, and the small fish near the river mouth attracted the large fish in the pass once caught by the locals.

2001 2006

Service de l'Urbanisme, Polynésie Française

Fig. 16. Aerial photos of the Temae regions in 2001 (left) and 2006 (right). In 2006 the lake border had been altered and the wetland had been filled in for the golf course. Also notice the sediment entering the lagoon at the river mouth.

There are some striking changes in the Temae region between 2001 and 2006 (Fig. 16). The entire wetland area north of Lake Temae has been filled in, and the lake itself has been artificially reinforced, most evident along the north edge of the lake. There is a distinct increase in sedimentation at river mouth which flows into the Ava Iti pass. There are fringing reefs in the areas directly adjacent to the deep water pass. Construction of the golf course began in 2005, and the picture on the right captures the golf course when it is about halfway complete.

11. Future Developments

The Moorea Golf Resort project has plans for additional major developments (fig. 17). A 5-star ultra-luxury 150-room beachfront hotel resort and spa will be added to the golf resort. Additionally, there are plans to build 115 mountain and beach residential villas. They will be 2-4 bedrooms each on plots ranging from 1,000m^2 to 2,500m^2 (mooreagolf-resort.com). According to an employee interviewed at the Moorea Golf Resort, construction of the hotel will begin this summer (2008). Once the hotel is complete, construction of the villas will begin. This is expected to happen in a couple of years.

Unfortunately, this means that the environmentally disastrous golf course was only the beginning of the project. Construction of the beachfront hotel is a major project and will increase sediment load on the coral and add to runoff contaminants. The villas will require extensive additional terracing of the hillsides. Additionally, Moorea does not have a sewage system, and all wastewater is treated in septic systems by hotels and the rest of the island. Septic systems are highly susceptible to overfilling and imbalance of its bacterial action and can allow untreated nutrients to enter the groundwater (Atkinson et al., 2003).

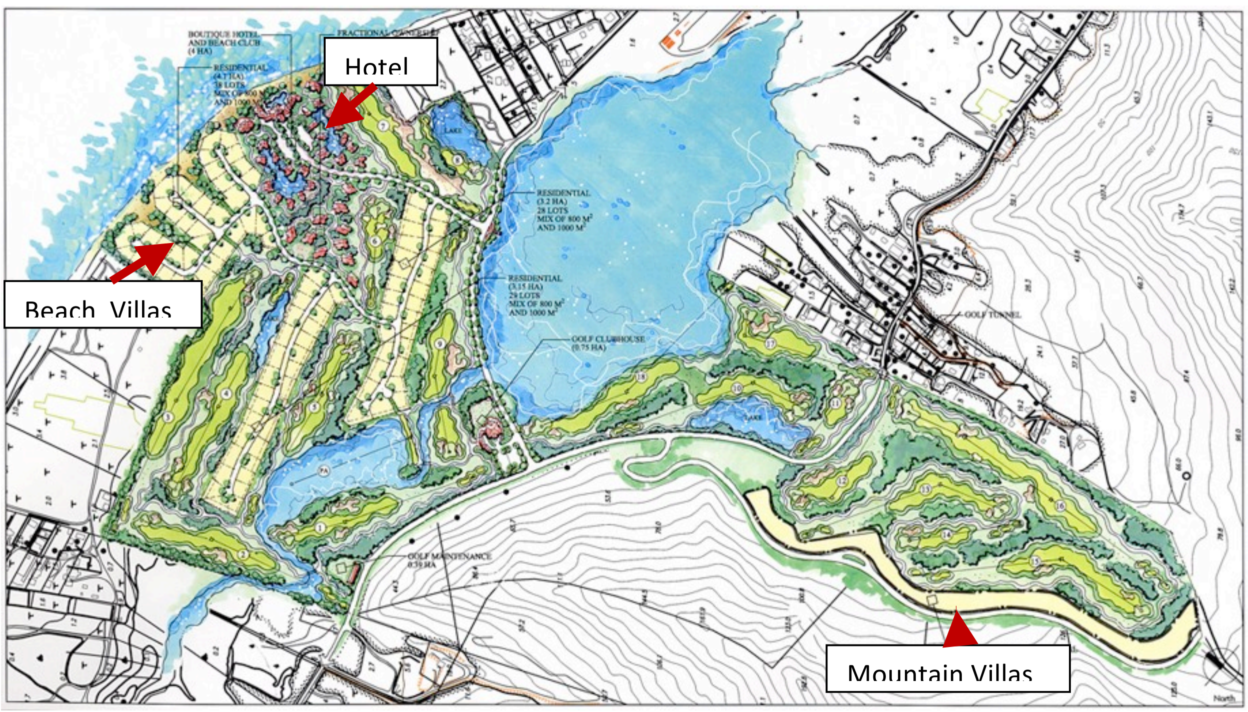


Fig. 17. Layout of future hotel and villas (Source: www.mooreagolf-resort.com)

12. Nicklaus Design Corporate

A letter was mailed to two of the corporate offices in the United States located in Florida and Utah to inquire about the design, development and maintenance of their golf courses.

A direct email address is not provided on the Nicklaus Design website; however, the website provides a submit form for questions. The request that was submitted inquired about future plans of the Moorea golf course, including the hotel and villas. This form was submitted in early April but a response was not received.

A representative from the Florida office, but not the Utah office, emailed a lengthy and amicable response to the mailed letter.

The main points were that the company:

> -strives to be as environmentally responsible as they can be in all situations and still satisfy the client's desires for a first-class golf course in the Nicklaus tradition of excellence
>
> -insures the least amount of chemicals and fertilizers that have to be used to maintain the facility
>
> -chooses proper soils and sands for proper drainage
>
> -emphasizes water savings, and
>
> -strives to save as many trees as they can, but that shade is an enemy of turf, so a balance must be achieved that will allow both to co-exist without excess stress being placed on each other,

but that in the end, it is the client, the membership, and the maintenance staff that determines what kind and how many pesticides and fertilizers are used on their golf course. They also "provide a [golf] course that should do well with the above considerations but they cannot dictate how their goals are achieved once the course is open for play", and "they can only trust that those philosophies or environmental sensitivity and stewardship will be followed".

Conclusion

This research project found that construction of the golf course has indeed caused observable changes in the lagoon. Further development will likely put additional strain on these sensitive ecosystems.

The development of the hotel and residential villas will undoubtedly be destructive to the marine habitat in the Aroa Marine Protected Area. There has already been a significant increase in sedimentation at the river mouth, and a disappearance of large fish in the Ava Iti pass right off the river mouth. Because of the proximity of the hotel site to the coast, chemicals that do not directly enter the lagoon would easily leech into the ground and enter the lagoon quickly through the aquifer. Marine Protected Areas were set aside in recognition of the importance of reef health and protecting the marine biodiversity of Moorea. The golf resort project and development methods are inconsistent with these goals.

There is already strong evidence of contamination by heavy metals from the golf course. Not only did the samples contain metals that do not originate in Moorea, but there was also a clear, consistent pattern showing the highest levels of multiple trace metals at the golf course, tapering off with increased distance from the golf course. This demonstrates that contaminants from the golf course are able to enter the lagoon. These findings raise concerns about the toxicity of metals on coral and other marine life.

It has been established that sediment can pose a serious threat to the survivability of coral. The additional terracing and new roads for future developments will increase the sediment load on the coral. The hotel in particular is being developed right on the water's edge. Large piles of loose, unsecured sediment were found throughout the site of the golf course and the same will probably be true of the hotel development site. If sedimentation can prevent a reef system from developing, it is not a stretch to say that it can prevent recovery of reefs and coral growth. Erosion and detritus entering the lagoon create an environment unsuitable for reef formation.

Recommendations

Because the golf course is already built and is operational, it is vital to employ more sustainable practices in order to limit ecological damage from maintenance of the grounds. The golf course should limit the use of fertilizers and pesticides to the minimum amount required. One way to reduce runoff is to design more efficient irrigation systems. This would also avoid overtaxing the island's limited water supply. Deciding to landscape with native and low-maintenance vegetation in future developments will also minimize the water usage and need for pesticides.

With the hotel likely to get underway this summer, it is urgent to develop environmentally sound methods for coastal development to avoid an ecological disaster. Efforts should be made to stabilize exposed soils and to design systems that minimize runoff. Project planning should incorporate Integrated Pest Management (IPM), as well as consider alternatives to terracing for the villas, such as stilting. Any process or design that may directly or indirectly harm reef life should be reevaluated.

With the well-being of the coral ecosystem at stake, perhaps the plans for developing the villas can be reconsidered. The exact degree of the impacts from these developments is unknown, but it is certain that there will be an impact, as there has already been, and the risks are too great to continue to develop carelessly. Thus, there should be continued monitoring of pollution and contaminants. Changes in the environment are also a good indication of ecosystem imbalance. The state of the Aroa Marine Protected Area and the development of the Moorea Green Pearl Golf Resort should be carefully observed.

Results from this study confirm that matter from the golf course has already entered the marine environment and has caused shifts in the offshore ecosystem. It must be recognized that the enormous scale of the resort development will affect the future direction of the ecosystem and that its current schema may not be in the best interest of Moorea.

APPENDIX

Additional photographs

Fig. A1. Abrupt interface of golf course and remaining wetland (a), tractor (the tractor is under a red umbrella) pushing dirt into the wetland (b), runoff (c), loose sediment (d),some tractors on site (e), and golf course edge and wetland (f), March/April 2008.

Fig. A2. Preparing the landscape for the golf course. Dredging and filling in of the lake (a) and (b), clearing of hillside (c), and pumping of lake (d). 2005-2006. Source: http://www.mooreagolf-resort.com.

Fig. A3. Views of the golf course open for play. Western portion of course (a), view from mountain above golf course, looking north (b), looking south from middle of course(c), sandpits in western portion. March/April 2008.

Aerial Photograph-1982

Fig. A4. Aerial photo of Temae region, 1982, Service de l'Urbanisme.

Letters to and from Nicklaus Design

This was the letter that was submitted to two Nicklaus Design corporate offices. ---- I received a return email from the Utah office.

Joy Shih
----- ----- Street
La Jolla, CA 92037
(xxx) xxx-xxxx
-----@ucsd.edu

3 May, 2008

Nicklaus Design
930 E. Chambers St. Unit 5, Building 1
Ogden, UT 84403

-and-

Nicklaus Design
11780 U.S. Highway One, Suite 500
North Palm Beach, FL 33408

Dear Sir or Madam,

I am researching golf courses and came across your website about Nicklaus Golf Course designs. I was really pleased that you take a "green" approach to your designs, which I think is great! In light of current attitudes and the need to be more environmentally conscious, I think your designs will be a benefit to all, including to the success of your business as well as the environment. If you would be willing to share what steps you have taken to make yourselves more environmentally friendly than typical golf courses, I would very graciously appreciate your willingness to share. For example, are you using alternatives to standard pesticides and herbicides? Or, have you chosen ones that are considered less harmful to both native wildlife and the environment? Do you incorporate IPM (integrated pest management)?

I am interested in this because I am a student at the University of California in San Diego and I am studying land-use. I am interested in more sustainable practices and protecting our environment. My personal view is that development- whether for real estate, tourism, agriculture, or virtually any other endeavor is inevitable, and it is how it is approached that is most important.

I hope other golf courses will eventually take your lead in a conscious approach to developing while minimizing the impact on the environment.

I have attached a list of fertilizers and chemicals commonly used by other golf courses. I would be very appreciative if you could take the time to share if you utilize any of these items, and also to list any alternatives you have chosen to use. I am particularly interested in your new golf course in Moorea in French Polynesia (the Moorea Green Pearl Golf Course) so information specific to that golf course would be very helpful and appreciated if it is any different.

I assure you I have no connection or intent to any policy or interest groups, I am inquiring for my own information as a student. If you have any questions or concerns, please contact me. Any information that you are willing to share with me would be much appreciated! Thank you very much for your time and willingness. Also if there is email contact information it would be much appreciated.

Best regards,

Joy Lily Shih

This is an attachment to a letter. I am a student and am following up on golf-course development. This is a list of commonly used materials on golf courses. Please indicate which of these you use, and also any alternatives you have chosen. Most of the trade names have been listed. As stated before, this is only for my interests as a student studying land use and development, and this information will not be shared with any outside sources, nor be used for any further purposes. Thank you very much!

Joy (xxx) xxx-xxxx -----@ucsd.edu			
	Use?	If known, what amount and frequency?	Alternative(s)?
2,4-D (2,4-Dichlorophenoxyacetic acid) (PAR III, Trillion, Tri-Kil, Killex, Weedaway Premium 3-Way XP Turf Herbicide)			
Aromatic petroleum solvents			
Atrazine			
Benfluralin (Benefin)			
Benomyl (Benlate)			
Bensulide (Betamec, Betasan, Benzulfide, Disan, Exporsan, Prefar, Pre-San, R-4461)			
Chlorothalonil (Bravo, Echo, Daconil)			
Chlorpyrifos (Dursban, Lorsban)			

Copper Sulfate (Bordeaux Mixture, Cheshunt Compound, Phyton 27)			
DCPA (Dacthal)			
Diazinon			
Dicamba (Banvel, Oracle, Vanquish)			
Diquat (Aquacide, Dextrone, Preeglone, Deiquat, Detrone, Reglone, Reglon, Reglox, Ortho-Diquat, Weedtrine)			
Disulfoton (Di-syston, Disystox, Frumin AL, Soilvirex)			
Dithane-44 (Maneb, Ziram)			
Ethylene dibromide (EDB)			
Iprodione (Kidon, Rovral, Chipco 26019, LFA 2043, NRC 910, DOP 500F, Verison)			
Isofenphos (Amaze, Oftanol, Pryfon)			
MSMA (onosodium methane arsonate, methyl arsonic acid monosodium salt (9CI))			
Maneb (Dithane M-22, Manesan, Manex, Manzate, Nereb, Newspor)			
Mecoprop (MCPP)			

Paraffin oil			
Pendimethalin (AC 92553, Accotab, Go-Go-San, Herbadox, Penoxalin, Prowl, Sipaxol, Stomp, Way-Up)			
Pentachlorophenol (Santophen, Pentachlorol, Chlorophen, Chlon, Dowicide 7, Pentacon, Penwar, Sinituho, Penta)			
Thiophanate-methyl (Domain, Duosan, Zyban, Benefit, Cleary's 3336)			
Thiram (AAtack, Arasan, Aules, Fermide 850, Fernasan, FMC 2070, Hexathir, Mercuram, Micropearls, Nomersan, Pomarsol, Puralin, Rezifilm, Rhodiasan Express, Spotrete, Tersan, Thiosan, Thiotex, Thiramad, Thirame, Thiuramin, Thirasan, Tirampa, Tiuramyl, TMTC, TMTD 50 Borches, Trametan, Tuads, Tulisan)			

Trichlorfon (Anthon, Bovinos, Briten, Chlorophos, Ciclosom, Dylox, Dipterex, Ditrifon, Dylox, Dyrex, Equino-Aid, Foschlor, Leivasom, Neguvon, Masoten, Trichlorophon, Trinex, Phoschlor, Proxol, Trichlorophene, Totalene, Tugon and Vermicide Bayer 2349)			
Xylene			
Please return to:			
Joy Shih			
----- -------- Street			
La Jolla, CA 92037			

Gmail by Google BETA

Joy Shih <------@gmail.com>

Your Letter

1 message

Jon Scott <-------@nicklaus.com> **Mon, May 19, 2008 at 3:01 PM**
To: -----@ucsd.edu

Joy,

I am the head of agronomic services for Nicklaus Design and your letter was forwarded to me for a response. First of all, thank you for your thoughtful comments on our golf course design philosophy after reviewing our Web site. We do strive to be as environmentally responsible as we can be in all situations and still satisfy the client's desires for a first-class golf course in the Nicklaus tradition of excellence. That can sometimes be a balancing act, but I think we do as good a job as anyone in the industry.

Your letter assumes that we are involved in the day to day maintenance operations at golf courses we design for our clients. In reality we are not. Our job is to design and to an extent oversee the construction of the golf course from the initial concept right through grow-in and opening. Our goal is to make sure the course is constructed according to guideline specifications we developed that will insure that the least amount of chemical and fertilizers have to be used to maintain the facility. That starts with choosing or modifying the soils for good drainage and rootzone aeration, and continues with the proper selection of greens sand and amendments. These are then assembled according to the accepted USGA protocol along with closely monitored quality control checks along the way by independent laboratories that have been certified by the USGA for testing the various components. We make sure that the right grasses are selected to do well in the environment where the golf course is being built with emphasis on water savings and pest resistance. We do this by checking the various research sites that independently evaluate the grasses around the world so we can match them up with the site and the theme of the golf course. We also pay special attention to the design of the irrigation and drainage systems which are done by design consultants we recommend to the client who are familiar with and supportive of our goals. By getting the right combination of sprinkler head coverage and pump efficiency, both water and power demand can be significantly reduced. We also try to design the least amount of highly maintained turf as possible to match wind conditions and the skill level of the client's intended golfers. To do this we utilize extensive acreage of natural type grasses that are not to be intensively maintained. These areas require water only for establishment and survival during prolonged dry spells, no fertilizer inputs, and very minimal spot herbicide treatments. Pest control is unnecessary and they may be mowed only once or twice in a whole growing season. If a site has trees, we strive to save as many as possible and advocate relocation and mitigation plantings for those that must be removed in the golf corridor. Unfortunately, shade is an enemy of healthy turf, so a balance has to be achieved that will allow both to co-exist without excess stress being placed on each other. Finally, we work hard to make our courses maintainable with minimal input from mowing machines. Again, this is done by reducing the highly maintained turf acreage. For instance, we use only a three tee system instead of a four or five commonly used by other designers. Our greens are sized on the average of around 4,000 sq. feet, about half what other designers commonly do. Our fairways seldom go over 30 acres and many times are less than 25. Maintained rough areas are usually around 50 acres or less. We fight to make golf courses less than 7,500 yards, but until the USGA scales back the golf ball that length keeps getting pushed up by clients eager to keep the golf course challenging for the better golfers. If Jack had his way, the ball would be returned to the 1990 range where 7,200 yard courses were all the challenge anyone needed. Unfortunately that decision is out of our hands.

What we ask of our clients during the grow-in and post-opening maintenance of the golf course is that they remain committed to an Integrated Pest Management philosophy using Best Management Practices. Healthy turf needs less water, not more, so we strive to encourage regular soil and tissue testing to make sure that only those supplemental nutrients that are needed to meet the turf needs are applied, and in minimal quantities to avoid runoff and excessive leaching. Other cultural practices such as aerification, verticutting, and topdressing are also encouraged as is the use of natural organic products wherever it makes sense to do so. Mowing with sharp blades lessens the exposure to fungal pests and keeps the plants from stressing as does maintaining the height at a level that is reasonable and not excessively low. Our greens and fairways are somewhat more contoured than some designers which allows a higher height of cut and slower ball speed to avoid rolling too far off the intended line on a miss-hit. Finally, we advise our clients to retain the services of a qualified golf course maintenance consultant who subscribes to our philosophies on the environment and sustainability. From time to time, some one from our staff will visit courses that display the Nicklaus name and renew that philosophy with the management and maintenance teams.

In the final analysis, it is the client, the membership, and the maintenance staff that determines what kind and how many pesticides and fertilizers are used on their golf course. We will have given them a course that should do well with minimal input from both, but we cannot dictate how they achieve our goals once the course is open for play. We can only trust that they will follow the lead that we have given them and carry on our philosophies of environmental sensitivity and stewardship.

Thanks again for your interest in our work and I wish you well with your project. I'm sorry I can't help you specifically with Morea as I have not visited that golf course and as far as I know it is under regular maintenance now. I can attest that it was constructed using the principles outlined above, as are all Nicklaus Design golf courses. If I can be of further help, please let me know.

Jon

Shih Letter.pdf
81K

Sampling Sites and Dates

	ID number		Date	Time	GPS location	Comments
1	TB3-24-1	Temae Beach 1	24-Mar	12:30	S 17° 29.943', W 148* 45.493'	Sunny
2	TB3-24-2	Temae Beach 2	24-Mar	13:00	S 17° 29.984', W 149* 45.576'	Partly Cloudy
3	TB3-27-1	Temae Beach 1	27-Mar	14:30	S 17° 29.943', W 148* 45.493'	Sunny
4	TB3-27-2	Temae Beach 2	27-Mar	15:00	S 17° 29.984', W 149* 45.576'	Sunny
5	TB4-4	Temae Beach1	4-Apr	17:00	S 17° 29.984', W 149* 45.576'	Few Clouds
6	AP3-28	Aroa	28-Mar	15:15	S 17° 28.430', W 149* 46.777'	Windy/Sunny
7	AP4-4	Aroa	4-Apr	13:30	S 17° 28.430', W 149* 46.777'	Sunny
8	AP4-6	Aroa	6-Apr	14:30	S 17° 28.430', W 149* 46.777'	Sunny
9	AP4-8	Aroa	8-Apr	13:30	S 17° 28.430', W 149* 46.777'	Sunny
10	LT4-4	Lake Temae	4-Apr	12:30	S 17° 28.977', W 149° 46.268'	Sunny
11	LT4-5	Lake Temae	5-Apr	14:00	S 17° 28.977', W 149° 46.268'	Sunny
12	LT4-7	Lake Temae	7-Apr	12:00	S 17° 28.977', W 149° 46.268'	Sunny
13	LT4-8	Lake Temae	8-Apr	10:00	S 17° 28.977', W 149° 46.268'	Sunny
14	RM4-4	Rivermouth	4-Apr	13:00	S 17° 28.555', W 149° 46.686'	Sunny, almost no wind
15	RM4-6	Rivermouth	6-Apr	14:00	S 17° 28.555', W 149° 46.686'	Sunny
16	RM4-8	Rivermouth	8-Apr	13:00	S 17° 28.555', W 149° 46.686'	Sunny
17	MT4-5	Motu Tiahura	5-Apr	14:00	S 17° 29.204', W 149°54.533'	Sunny, Strong Current 45°NE
18	MT4-7	Motu Tiahura	7-Apr	16:30	S 17° 29.204', W 149°54.533'	Cloudy
19	MT4-8	Motu Tiahura	8-Apr	10:30	S 17° 29.204', W 149°54.533'	Sunny

Table A1. Sampling dates, 2008.

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