The effect of causeway construction on seagrass meadows in the Western Pacific — a lesson from the ancient city of Nan Madol, Madolenihmw, Pohnpei, FSM

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Two seagrass meadow sites were chosen at Nan Madol adjacent to the now permeable remnants of an ancient causeway constructed 500 to 700 years ago: one immediately on the shoreward side of the causeway, and one immediately on the seaward side. The shoreward site had greater seagrass cover, canopy height, algal abundance, and epiphyte abundance and lower species diversity (both seagrass and macro-algae), as well as muddier sediments than the seaward site. The abundance of associated fauna did not appear to differ between sites, although the composition of the faunal communities was different. On the seaward site, average epiphyte cover was less than one-tenth the epiphyte cover of that on the shoreward side. *Halimeda* species were the most common algae on the seaward side, while on the shoreward side *Hypnea* species were dominant. *Cymodocea rotundata* was the dominant seagrass species (54% of seagrass cover) on the seaward site, but was absent on the shoreward site, which was dominated by *Thalassia hemprichii* (84%) and *Enhalus acoroides* (16%). There was no difference in salinity between the two sites. Sediments had a higher proportion of fine mud shoreward. The beche-de-mer, *Holothuria atra*, was common on the seaward side of the causeway, but not on the shoreward side. The causeway is open to water flow at all tide heights and does not appear to influence water height in any way. The effects of even this simple permeable barrier on seagrass meadows are evident and include differences in seagrass species, algal species, and fauna. We discuss the management lesson from this historic location for present-day Pacific island causeway developments.

Key words: Seagrass, Causeway, Pacific island, Management.

INTRODUCTION

POHNPEI is the largest island in the Federated States of Micronesia and is approximately 5 degrees north of the equator. It is a high island with a fringing reef and extensive coastal reef-flats and seagrass meadows.

There are three species of seagrass in the waters surrounding Pohnpei: *Cymodocea rotundata, Thalassia hemprichii* and *Enhalus acoroides* (McDermid and Edward 1999), all typical of coral reef flat communities in the western Pacific (Coles *et al.* 2003a). Pohnpei seagrasses are presently being studied as part of a global seagrass monitoring programme (www.seagrassnet.org and www.seagrasswatch.org) to analyse long-term trends and changes, and to transfer monitoring and mapping skills to local seagrass groups. Part of the rationale of this programme is to study both pristine and impacted sites. Nan Madol, on the south-east coast of Madolenihmw municipality on Pohnpei Island, was targeted as a site where long-term historical impacts are evident.

Nan Madol reportedly was the ceremonial and political seat of the Sau Deleur dynasty which united Pohnpei's estimated 25 000 people in late prehistoric times (Ayres 1990a). Nan Madol forms an archaeological district covering more than 18 km². It includes the stone architecture built up on a coral reef flat along the shore of Temwen Island (Fig. 1). The site core, with its stone walls, encloses an area approximately 1.5 km long by 0.5 km wide and is composed of ninety-two human-made islets constructed on the reef flat. Nan Madol was built over an extended period of time with megalithic architecture characterized by long, naturally prismatic log-like basalt stones. Archaeological data indicates active construction on Nan Madol occurred from approximately A.D. 500 to the mid-1500s (Ayres 1990b, 1992). Extensive seagrass meadows are found on Pohnpei's sheltered inner reef platforms and occur to the north and south of Nan Madol. The Pohnmweirok rock causeway, which was likely used to access Peiniot islet for burial or other ceremonial purposes, divides the seagrass meadow to the north of the main ancient city into two parts (Figs 1 and 2).

Causeway construction is common in the western Pacific island countries, with extensive construction occurring for transport connections after World War II. Changes in seagrass meadow distributions have been observed near these causeways due to changes to water and sediment movement and this is well recognized as a

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PACIFIC CONSERVATION BIOLOGY Vol. 11: 212–20. Surrey Beatty & Sons, Sydney. 2005.

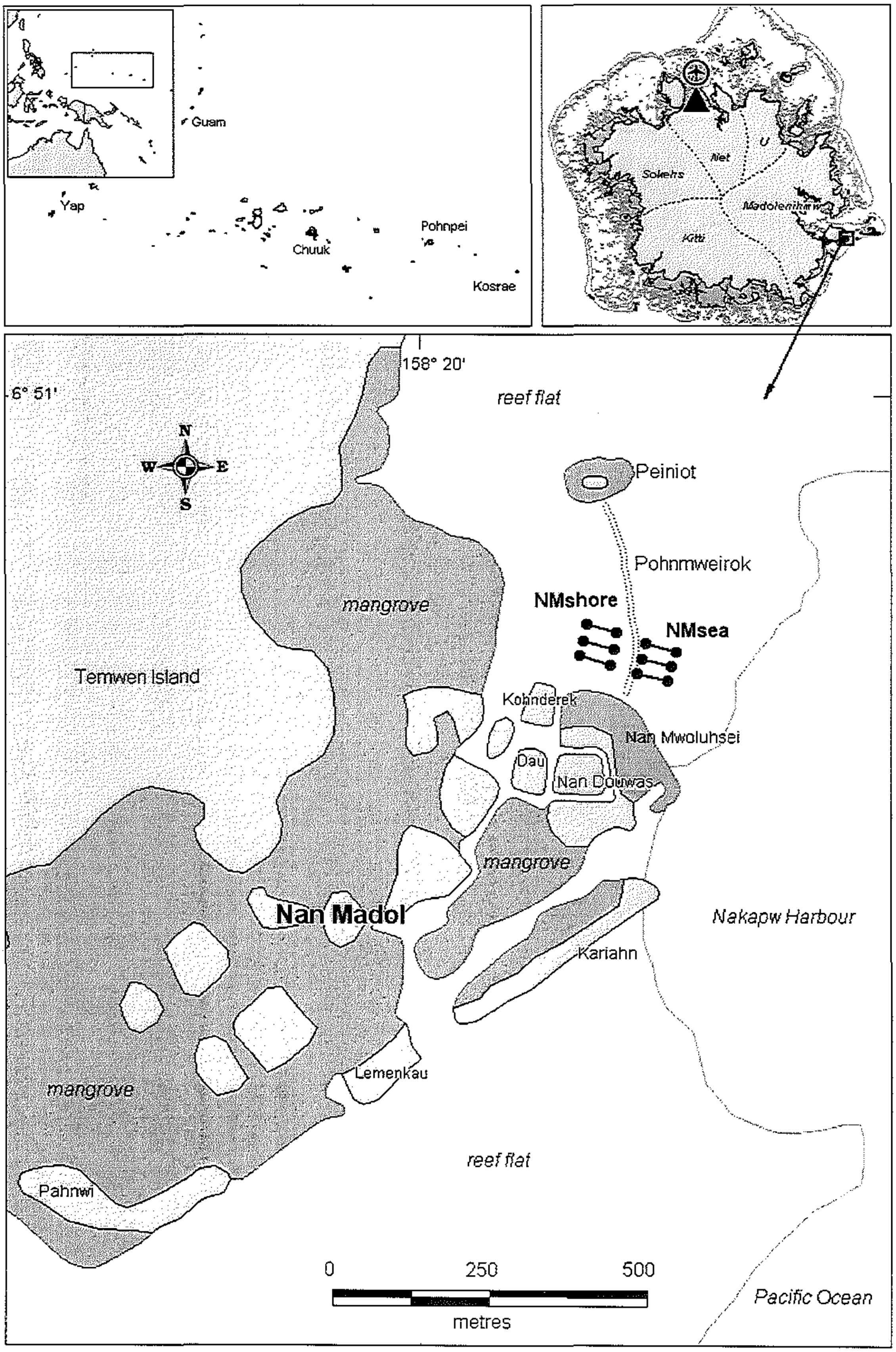

Fig. 1. The location of Nan Madol on Pohnpei (Federated States of Micronesia), the core Nan Madol archaeological district with the Pohnmweirok rock causeway to the Peiniot islet and the location of the two sampling sites (NMsea and NMshore).

Fig. 2. Pohnmweirok rock causeway which was constructed 500 to 700 years ago and was likely to have been used to access the Peiniot islet for burial or other ceremonial purposes. The open rock causeway allows water flow at all tides but acts to buffer wave action (right of photograph) and to slow the velocity of tidal flows.

negative environmental consequence (Maragos 1993; Coles 1996). It is uncertain whether the changes to habitats occurring near these relatively recent causeways have stabilized to a new equilibrium.

The causeway at the ancient city of Nan Madol was constructed 500 to 700 years ago, and it can be safely assumed that the adjacent seagrass meadows are no longer changing as a result of the changes in water movement and sediment that would have occurred starting at the time of construction. The causeway is now an open rock structure (Fig. 2) that allows water flow at all tides, but acts to buffer wave action and to slow the velocity of tidal flows.

Seagrasses have been documented throughout the western Pacific (Coles and Kuo 1995; Coles and Lee Long 1999; McDermid and Edward 1999; Coles *et al.* 2003a), and the distribution of species on a regional scale investigated. Less well studied and understood are the factors that influence reef platform distribution of these tropical species and the long-term effects on seagrass distribution of the changes made in providing infrastructure for urban and tourist development.

In this paper we use Seagrass-Watch methodology (McKenzie and Campbell 2002) to compare aspects of the seagrass meadow on either side of the Pohnmweirok rock causeway. The differences can be used to support a case to limit construction of new causeways between islands without an analysis of the likely outcome for reef platform seagrass communities; we suggest modifications to causeway construction. We also describe the local reef flat species distribution and composition and speculate on the factors controlling distribution of reef flat seagrass and on the appropriateness of using the Seagrass-Watch rapid assessment methods for monitoring and comparing the habitat characteristics of seagrass meadows.

MATERIALS AND METHODS

Seagrass abundance and habitat characteristics at Nan Madol were investigated on the 17th June 2002 using a rapid assessment technique known as Seagrass-Watch, as described in McKenzie and Campbell (2002) and based on McKenzie *et al.* (2001) developed in tropical Australia.

A 50 m × 50 m site was chosen within each of the representative intertidal seagrass communities on either side of the Pohnmweirok rock causeway, Nan Madol. Sites were placed within a relatively homogeneous region (low variability, even topography) of each seagrass meadow and as close to the causeway as practicable. Within each site, three replicate transects were laid parallel to each other, 25 m apart and perpendicular to the causeway (Fig. 1). Site NMsea was placed on the seaward side of the causeway, and site NMshore was on the shoreward side. Along each transect, observers recorded seagrass habitat characteristics (including per cent seagrass cover, seagrass species composition, canopy height, epiphyte cover, algae cover, algae composition, sediment type and associated fauna) within a 0.25 m^{-2} quadrat (50 cm × 50 cm) at 5 m intervals (11 quadrats per transect, 33 quadrats per site).

Estimates of the total per cent cover of seagrass within the quadrat were standardized using the per cent cover photo standards from McKenzie and Campbell (2002). Seagrass species within the quadrat were identified and the per cent contribution of each species to the total cover determined. Seagrass species were identified according to Kuo and Den Hartog (2001). Voucher specimens of each seagrass species were collected for later verification.

Canopy height of the dominant species in the seagrass community was measured (from the sediment to the leaf tip) using a ruler. The method used was to ignore the tallest 20% of leaves of the dominant species and to haphazardly select three to five leaf blades from the remainder. The cover of epiphytes was recorded by estimating the per cent of the total leaf surface area covered by epiphytes. Percent cover of non-epiphytic algae in each quadrat was estimated using the same visual technique used for seagrass cover. Algae were identified according to Cribb (1996).

Field descriptions of sediment type were described using visual estimates of grain size: shell grit, rock gravel (>2 000 μm), coarse sand (>500 μm), sand (>250 μm), fine sand (>63 μm) and mud (<63 μm). Sediment categories were determined by the dominant sediment type (e.g., sand/mud = more sand than mud). Salinity was measured in situ with a refractometer.

The abundance/presence of associated fauna within each quadrat was recorded. Fauna were identified to the highest taxonomic level possible in the field.

To provide a permanent record/archive of the site, photographs were taken at the 5 m, 25 m and 45 m quadrats along each transect. A global positioning system (GPS) was used to record the geographic location of each transect.

For analysis, quadrat measures were pooled across each site (as there was no significant difference between transects) and Two-sample T-tests were used to compare between sites.

RESULTS

The seagrass communities on either side of Pohnmweirok rock causeway, Nan Madol, were distinctly different (Fig. 3), even though at their closest points they are only 46 meters apart. The shoreward site had higher seagrass cover, greater canopy height, higher algal abundance, lower species diversity (of both seagrass and macro-algae), higher epiphyte abundance and muddier sediments. The abundance of associated macrofauna did not differ between sites, although the faunal communities were different.

Mean per cent cover of seagrass was significantly higher in the shoreward site (NMshore mean cover = 85.1 ± 2.6% for all quadrats pooled) than the seaward site (NMsea mean cover = 56.5 ± 2.6% for all quadrats pooled) (Fig. 4) ($T = -7.79$, $df = 64$, $p < 0.05$). The seaward site (NMsea) seagrass composition was dominated by *Cymodocea rotundata* mixed with *Thalassia hemprichii*, and less than 1% *Enhalus acoroides*. The shoreward site (NMshore) was dominated by *Thalassia hemprichii*. *Enhalus acoroides* contributed approximately 16% to the total species composition on the shoreward site and *Cymodocea rotundata* was absent.

a

b

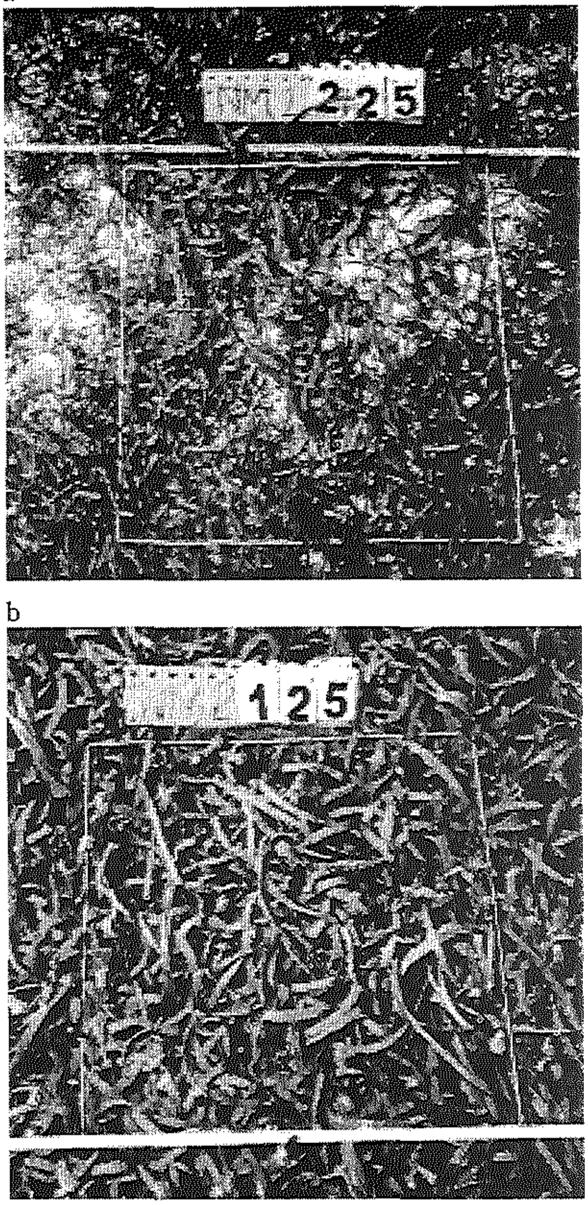

Fig. 3. Photographs of representative seagrass habitats from the a. seaward site (NMsea), and b. shoreward site (NMshore). Quadrats in photographs are 50 cm by 50 cm.

Canopy height of the dominant species was significantly higher at the shoreward site dominated by *Thalassia hemprichii* than at the seaward site dominated by *Cymodocea rotundata* ($T = -2.51$, $df = 54$, $p = 0.02$) (Fig. 4).

Macro-algae abundance (cover) was significantly higher shoreward than seaward (mean = 17.8% and 7.4%, respectively) ($T = -3.29$, $df = 42$, $p < 0.05$) (Fig. 4). Macro-algae at the seaward site (NMsea) were more diverse, but with a lower cover than the shoreward site (NMshore). The macro-algal community at the shoreward site was dominated by *Halimeda opuntia* (16%) with some *Hypnea* and *Dictyota*. The macro-algal community at the seaward site was dominated by *Hypnea*

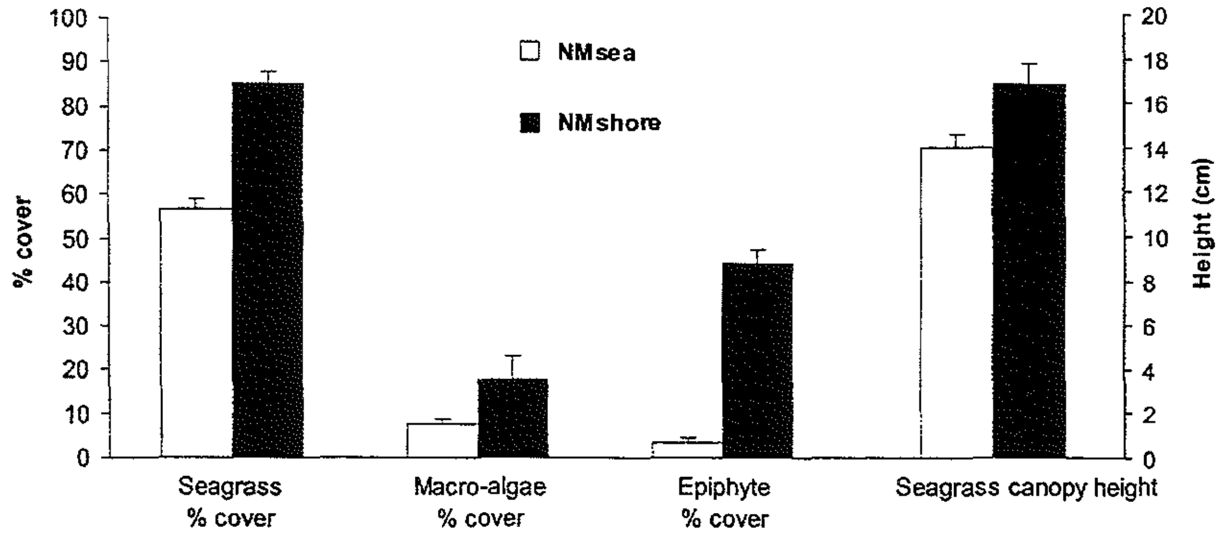

Fig. 4. Per cent cover of seagrass, leaf epiphytes and macro-algae, and seagrass canopy height for the seaward (NMsea) and the shoreward (NMshore) sites at Nan Madol.

(~3% cover), *Halimedia opuntia* and *Padina tenuis*, with small amounts of *Turbinaria ornata, Laurencia* and *Caulerpa*.

Table 1. Mean percentage cover (± standard error) of macro-algae at each site.

Algae	NMsea	NMshore
Caulerpa spp.	0.06 ± 0.06	absent
Dictyota bartayressi	0.24 ± 0.24	0.15 ± 0.15
Halimeda opuntia	1.60 ± 0.52	16.00 ± 4.00
Hypnea spp.	2.61 ± 1.21	2.30 ± 0.89
Laurencia spp.	0.003 ± 0.001	absent
Miscellaneous brown	0.45 ± 0.243	0.24 ± 0.19
Padina tenuis	1.11 ± 0.63	absent
Turbinaria ornata	0.16 ± 0.12	absent
Miscellaneous turf	absent	0.15 ± 0.15

Epiphyte cover was also significantly higher at the shoreward site than the seaward ($T = -9.52$, $df = 40$, $p < 0.05$, mean 3.4% and 44.5% at seaward and shoreward respectively) (Fig. 4).

Sediments were significantly muddier at the shoreward site than the seaward. The shoreward site was characterized by mud/fine sand, while the seaward was predominantly coarse sand/shell (Fig. 5). Salinity was the same at each site.

Associated fauna differed between sites. Significantly more *Holothuria atra* were present in the seaward site (Two-sample T-test $T = 2.17$, $df = 41$, $p = 0.036$). However, an unidentified species of holothurian, was more abundant at

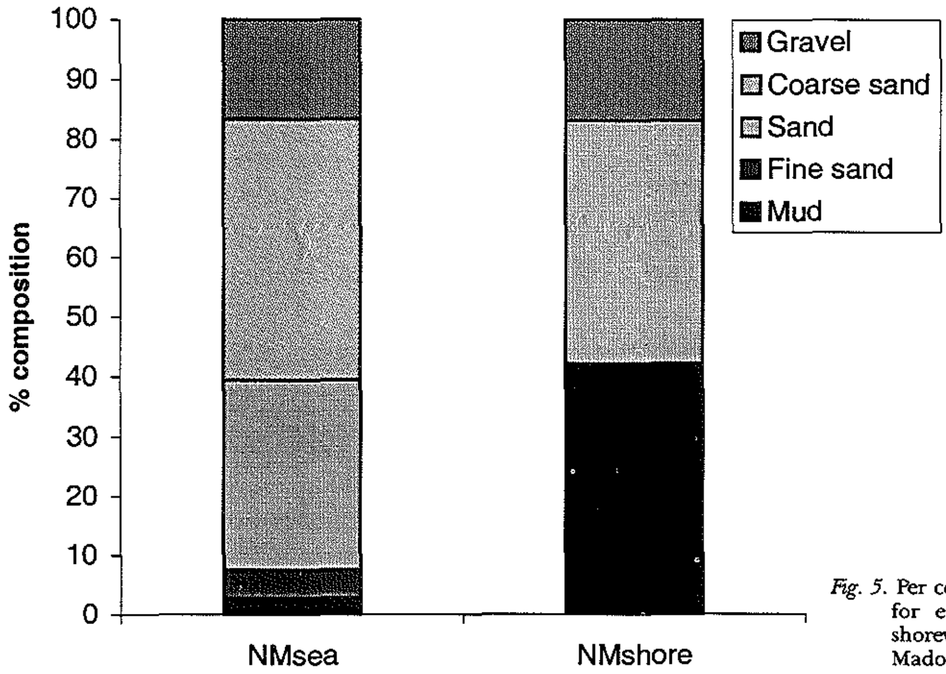

Fig. 5. Per cent composition of sediments for each seaward (NMsea) and shoreward (NMshore) site at Nan Madol.

the shoreward site (NMshore). The abundance of sponges was highly variable within and not significantly different between sites (Two-sample T-test T = 1.54, df = 64, p = 0.13).

DISCUSSION

The seagrass meadow at Nan Madol is part of an extensive reef platform meadow. The gross topography of the meadow is set by the underlying reef platform that slopes gently upward from the seaward margin to the mangrove-lined shore. Our experience of these environments from the global seagrass monitoring programme with reef platform sites in nine countries is that the species and morphology are relatively homogeneous across the platform and change, if it occurs, is either gradual or associated with a topographic feature (e.g., a hole in the platform and deeper water). While it is not easy to set a control or reference site as a comparison, the nearest reef platform site in the SeagrassNet (global seagrass monitoring programme) at Pohnpei (approximately 15 kilometers away) is a *Thalassia hemprichii* dominated meadow that shows no marked changes in seagrass composition or characteristics (approximately 20% change in mean cover across the entire reef platform) and certainly not the abrupt change evident at Nan Madol.

The Nan Madol meadow in the region of our study had no obvious topographic features that would lead to changes in seagrass composition apart from the existence of the causeway. It is reasonable, in our opinion, to assume that in the absence of the causeway, seagrass species composition and cover would have been evenly distributed with possibly small changes as any effect of wave action from the distant reef edge dissipated.

The influence of the causeway at Nan Madol on the seagrass meadow morphology is quite dramatic. There is significantly greater seagrass abundance on the shoreward side. The species composition is different with a dominance of *Thalassia hemprichii* on the shoreward side and *Cymodocea rotundata* on the seaward side. Canopy height is greater on the shoreward side. Visually, the meadows appear quite different as the presence of the large, broad-leafed *Enhalus acoroides* and the higher levels of epiphytic algae on the shoreward meadow provide a darker coloration compared with the seaward *Cymodocea rotundata* dominated meadows. The change in species composition from a *Thalassia hempichii* and *Enhalus acoroides* dominated community in the shoreward muddy sediments to a *Cymodocea rotundata* and *Thalassia hemprichii* dominated community in the seaward sand sediments is consistent with observed seagrass community changes along siltation gradients in south-east Asia (Terrados *et al.* 1998). *Cymodocea rotundata* is more sensitive to siltation than *Enhalus acoroides* (Terrados *et al.* 1998), which most likely explains its absence on the shoreward part of the meadow.

The construction of a causeway would have had four main effects:

1. Initially some immediate damage to the seagrass meadow would have occurred from construction. Given the time that has elapsed, this is unlikely to have left a measurable signature;
2. The causeway obstructs part of the wave movement that, during storms, could influence the type and morphology of seagrass meadows. Obstruction of wave movement may have caused major changes initially, with less effect as the causeway lost its structural integrity;
3. The causeway slows the escape of water from the reef platform as the tide falls, allowing for a pooling effect and slower movement of water thus increasing the accumulation of fine-grained sediments and allowing the persistence of long-bladed seagrass; and,
4. The causeway may limit access to the shoreward side by some herbivores that would have to move off the reef platform at low tide and different grazing pressures would lead to different stable seagrass communities.

For seagrasses to establish, sheltered conditions (reduced wave action) are often necessary (Lee Long *et al.* 1993; Dan *et al.* 1998; van Katwijk and Hermus 2000). Seagrass meadows can themselves reduce current velocity (Fonseca and Fisher 1986; Koch and Gust 1999), attenuate wave energy (Fonseca and Cahalan 1992; Koch 1996), change the level of turbulence in the water (Worcester 1995; Koch and Gust 1999), and enhance light availability by promoting the deposition of suspended sediments (Kemp *et al.* 1984; Short and Short 1984). As a result, there is a complex feedback relationship between seagrasses and the physical hydrology of the habitat they colonize.

Water flow affects almost all biological, geological and chemical processes in seagrass ecosystems at scales from the smallest (physiological and molecular) to the largest (meadow wide). The pollination of seagrass flowers depends on currents and the turbulence around these reproductive structures to transport pollen between male and female flowers (Ackerman 1986:1997). Without interconnectivity between meadows, cross-pollination will not occur and species composition and genetic diversity may be affected. Similarly, without current flows, vegetative material and seeds will not be transported to new areas, and species will not be exchanged between meadows. Factors such as the photosynthetic rate of seagrasses depend on the thickness of the diffusive boundary layer (Koch 1994) that is determined by current flow, as is the sedimentation rate. Both influence growth rates of seagrass, survival of seagrass species and overall meadow morphology. Some fauna (Murphey and Fonseca 1995) and attached epiphytic algae found in seagrass meadows survive because of the low current environments created by the presence of the vegetation.

The explanation for the differences in seagrass species abundance on either side of the causeway at Nan Madol is undoubtedly complex. All three species are common reef flat inhabitants in the Pacific (Coles and Kuo 1995; Green and Short 2003). *Enhalus acoroides* differs from other seagrass species in that pollination occurs above water and the plant must be able to extend above the water surface to sexually reproduce. Pollen movement could be disrupted by wave action and a strong current so this species is more likely to occur where water pools and is commonly found abutting mangrove forests in the Pacific islands. *Cymodocea rotundata* will colonize exposed reefs and is found in areas of high current. It is common in locations such as Torres Strait (Coles *et al.* 2003b) and the Great Barrier Reef (Lee Long *et al.* 1993; Short *et al.* 2001) where strong currents occur. It may simply be out-competed in the shoreward site.

Canopy height may be greater in the shoreward site because the pooling water remains deeper at low tide than on the seaward site, where water drains off the reef platform. Low tide exposure in this region close to the equator can lead to UV-B radiation damage to leaves (Short and Neckles 1999), reducing their length. The increased canopy height may also result from the muddier sediments providing a more conducive environment for seagrass growth on the shoreward side. Muddier sediments may also explain the greater abundance of seagrasses on the shoreward side and the change in species composition between areas of fine silty sediments and coarse sand dominated sediments.

As many as 154 species of fish and invertebrates feed directly on seagrass tissue and many more feed on epiphytic algae or shelter from predation among seagrass leaves (Klumpp *et al.* 1989). It is likely the changes in the seagrass canopy and species composition would influence the number and diversity of the fauna.

Causeways are common in the Pacific island countries and concern has been expressed regarding their effect on benthic communities (Maragos 1993). Road construction in sensitive environments continues, particularly in countries such as the Republic of Palau (Maragos 1993; Coles 1996). Tropical seagrass meadows support many juvenile fish and invertebrates (Coles *et al.* 1993), and changes even at small scales may have an effect on the size of populations that contribute to the food source for local fisheries.

The changes at Nan Madol have lessons for modern day causeway builders that we can offer with the benefit of considerable hindsight. When the causeway was constructed, 500 to 700 years ago, it is unlikely the concept of food security and its management would include the same emphasis on habitat protection and sustainability as it would today. Population density of people was likely to have been low and pressures on sea turtle, invertebrate and fish communities and their habitats to provide food would have been much less than at present. Transport infrastructure construction was limited to what could be made by hand. The idea that blocking the water flow across a reef platform could modify a seagrass habitat and change the type and number of animals and plants it could support would have been unlikely to have influenced the design of the causeway.

It is to be hoped that a similar project at Nan Madol today would be subject to some level of impact review and environmental design criteria. A precautionary principle should be applied. Certainly a causeway construction such as this one, if it were planned in most developed countries today, would trigger numerous legislative constraints. It would require at the least a permit to allow for the damage of marine plants during construction (see Coles and Fortes 2001) and the issue of that permit would require a design that would minimize the possibility of detrimental impacts to the area and the surrounding seagrass meadows. The design would be expected to include sufficient culverts to maintain existing water flows and flow rates. Culvert design would have to be justified in terms of maintaining natural flows at different tidal heights. We know of no specific advice available for culvert design to allow for the movement of plant propagules; however, general advice for fisheries is available (see Cotterell 1998). It is possible, given the perceived importance of seagrasses, that permission would be refused. A bridge on piers would be preferable. As seagrass scientists we would hope that a causeway such as the one built at Nan Madol would be refused construction today.

The Seagrass-Watch method used in this exercise is part of a broader western Pacific programme initiative, designed to monitor changes in seagrass meadows at a multi-country or regional spatial scale and at a climate change temporal scale (Short *et al.* 2002, www.seagrassnet.org). The Seagrass-Watch methods are a sub-set of the broader programme and are designed to be rapid and completed with only simple technology, ideal for local schools and community groups. The purpose of developing the Seagrass-Watch approach — it has been widely used in northeastern Australia (McKenzie *et al.* 2000, 2001) — has been to bring local citizens into a discussion of managing habitat protection and the underlying issues by demonstrating how powerful a simple monitoring method can be in comparing sites and in revealing local trends. Seagrass-Watch results may not answer every question. Fisheries science assistance may be necessary to fully understand impacts of change in seagrasses on local food webs. Seagrass-Watch does, however, provide a simple and rapid method of quantifying seagrass meadow characteristics and this can be used as a surrogate for monitoring impacts on broader marine biodiversity. The Seagrass–Watch monitoring method can provide useful information sufficient to influence decision making in the coastal zone in ways that may have an enormous long-term beneficial outcome.

ACKNOWLEDGEMENTS

This work was in part supported by the David and Lucile Packard Foundation, the University of New Hampshire, the Australian Cooperative Research Centre Program through the CRC Reef Research Centre, and the Department of Primary Industries & Fisheries, Queensland.

REFERENCES

Ackerman, J. D., 1986. Mechanistic implications for pollination in the marine angiosperm *Zostera marina*. *Aquat. Bot.* **24:** 343–53.

Ackerman, J. D., 1997. Submarine pollination in the marine angiosperm *Zostera marina* (Zosteraceae). I. The influence of floral morphology on fluid flow. *Amer. J. Bot.* **84:** 1099–109.

Ayres, W. S., 1990a. Pohnpei's Position in Eastern Micronesian Prehistory, *Micronesica*, Supplement 2: Proceedings, Indo Pacific Prehistory Association, Guam. Pp. 187–212.

Ayres, W. S., 1990b. Mystery Islets of Micronesia. *Archaeology* Jan–Feb 1990. Pp. 58–63.

Ayres, W. S., 1992. Nan Madol, Pohnpei. SAA Bulletin. 10 Nov. 1992. Society for American Archaeology.

Coles, R. G., 1996. Coastal Management and Community Coastal Resource Planning in the Asia Pacific Region. A report of Churchill Fellowship sponsored study April — July 1996. http://www.churchilltrust.com.au

Coles, R. G. and Fortes, M. D., 2001. Seagrass protection policy. Pp. 445–64 *in* Global Seagrass Research Methods ed by F. T. Short and R. G. Coles. Elsevier Science BV, Amsterdam.

Coles, R. G. and Kuo, J., 1995. Seagrasses. Pp. 39–57 *in* Marine and Coastal Biodiversity in the Tropical Islands Pacific Region. Vol 1: Species systematics and information management priorities. Proceedings of two workshops held at the East-West Center, Honolulu, in November 1994 ed by J. E. Maragos, M. N. A. Peterson, L. G. Eldredge, J. E. Bardach and H. F. Takeuchi. East-West Center, Honolulu.

Coles, R. G. and Lee Long, W. J., 1999. Seagrass. Pp. 21–46 *in* Marine and Coastal Biodiversity in the Tropical Islands Pacific Region. Vol 2: Population, development and conservation priorities. Proceedings of two workshops held at the East-West Center, Honolulu, in November 1994 ed by L. G. Eldredge, J. E. Maragos, P. F. Holthus and H. F. Takeuchi. East-West Center, Honolulu.

Coles, R. G., Lee Long, W. J., Watson, R. A. and Derbyshire, K. J., 1993. Distribution of seagrasses, and their fish and penaeid prawn communities, in Cairns Harbour, a tropical estuary, northern Queensland, Australia. *Aust. J. Mar. Freshwater Res.* **44:** 193–210.

Coles, R. G., McKenzie, L. J., Campbell, S. J., Fortes, M. and Short, F. T., 2003a. The seagrasses of the western Pacific islands. Pp. 177–86 *in* World Atlas of Seagrasses ed by E. P. Green and F. T. Short. Prepared by the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley. USA.

Coles, R. G., McKenzie, L. J. and Campbell, S. J., 2003b. The seagrasses of eastern Australia. Pp. 119–33 *in* World Atlas of Seagrasses ed by E. P. Green and F. T. Short. Prepared by the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley. USA.

Cotterell, E., 1998. Fisheries Guidelines for the Design of Stream Crossings — Fish Habitat Guideline FHG 001. State of Queensland, Department of Primary Industries, 37 Pp.

Cribb, A. B., 1996. Seaweeds of Queensland: a naturalist's guide. The Queensland Naturalist's Club Inc., Brisbane. 130 Pp.

Dan, A., Moriguchi, A., Mitsuhashi, K. and Terawaki, T., 1998. Relationship between *Zostera marina* beds and bottom sediments, wave action offshore in Naruto, southern Japan. *Fish. Eng.* **34:** 299–304.

Fonseca, M. S. and Cahalan, J. A., 1992. A preliminary evaluation of wave attenuation by four species of seagrass. *Est. Coast. Shelf Sci.* **35:** 565–76.

Fonseca, M. S. and Fisher, J. S., 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. *Mar. Ecol. Prog. Ser.* **29:** 15–22.

Green, E. P. and Short, F. T. (eds.), 2003. World Atlas of Seagrasses. University of California Press, Berkeley, USA. 286 pp.

Kemp, W. M., Boynton, W. R., Twilley, R. R., Stevenson, J. C. and Ward, L. G., 1984. Influences of submersed vascular plants on ecological processes in the upper Chesapeake Bay. Pp. 367–94 *in* The Estuary as a Filter ed by V. S. Kennedy. Academy Press, New York.

Klumpp, D. W., Howard, R. K. and Pollard, D. A., 1989. Trophodynamics and nutritional ecology of seagrass communities Pp. 394–458 *in* Biology of Seagrasses ed by A. W. D. Larkum, A. J. McComb and S. A. Shepherd. Elsevier, Amsterdam New York. 841 Pp.

Koch, E. W., 1994. Hydrodynamics, diffusion-boundary layers and photosynthesis of the seagrasses *Thalassia testudinum* and *Cymodocea nodosa*. *Mar. Biol.* **118:** 767–76.

Koch, E. W., 1996. Hydrodynamics of a shallow *Thalassia testudinum* bed in Florida, USA. Pp. 105–09 *in* Seagrass Biology: Proceedings of an International Workshop. Rottnest, Australia, 25–29 January, 1996 ed by J. Kuo, R. C. Phillips, D. I. Walker and H. Kirkman. Faculty of Science, University of Western Australia, Nedlands, Western Australia.

Koch, E. W. and Gust, G., 1999. Water flow in tide- and wave-dominated beds of the seagrass *Thalassia testudinum*. *Mar. Ecol. Prog. Ser.* **184:** 63–72.

Kuo, J. and Den Hartog, C., 2001. Seagrass taxonomy and identification key. Chapter 2. Pp. 31–58 *in* Global Seagrass Research Methods ed by F. T. Short and R. G. Coles. Elsevier Science B.V., Amsterdam.

Lee Long, W. J., Mellors, J. E. and Coles, R. G., 1993. Seagrasses between Cape York and Hervey Bay, Queensland, Australia. *Aust. J. Mar. Freshwater Res.* **44:** 19–32.

Maragos, J. E., 1993. Impact of coastal construction on coral reefs in the U.S.-affiliated Pacific islands. *Coastal Man.* **21**(4): 235–70.

McDermid, K. J. and Edward, A., 1999. Seagrass community composition and biomas at Nahpali Island, Pohnpei. *Micronesica* **31**(2): 225–62.

McKenzie, L. J., Campbell, S. J. and Roder, C. A., 2001. Seagrass-Watch: manual for mapping and monitoring seagrass resources by community (citizen) volunteers. Queensland Fisheries Service, NFC, Cairns. 94 Pp.

McKenzie, L. J. and Campbell, S. J., 2002. Seagrass-Watch: manual for community (citizen) monitoring of seagrass habitat — western Pacific edition. Queensland Fisheries Service, NFC, Cairns. 43 Pp.

McKenzie, L. J., Lee Long, W. J., Coles, R. G. and Roder, C. A., 2000. Seagrass-Watch: Community based monitoring of seagrass resources. *Biol. Mar. Medit.* 7(2): 393–96.

Murphey, P. L. and Fonseca, M. S., 1995. Role of high and low energy seagrass beds as nursery areas for *Penaeus duorarum* in North Carolina. *Mar. Ecol. Progr. Ser.* **121:** 91–98.

Short, F. T. and Neckles, H. A., 1999. The effects of global climate changes on seagrasses. *Aquatic Botany* **63:** 169–96.

Short, F. T., Coles, R. G. and Pergent-Martini, C., 2001. Global Seagrass Distribution. Pp. 5–30 *in* Global Seagrass Research Methods ed by F. T. Short and R. G. Coles. Elsevier Science B.V., Amsterdam.

Short, F. T., McKenzie, L. J., Coles, R. G. and Vidler, K. P., 2002. SeagrassNet Manual for Scientific Monitoring of Seagrass Habitat. Queensland Department of Primary Industries, QFS, Cairns, Australia. 56 Pp.

Short, F. T. and Short, C. A., 1984. The seagrass filter: Purification of estuarine and coastal waters. Pp. 395–413 *in* The Estuary as a Filter ed by V. S. Kennedy. Academy Press, New York.

Terrados, J., Duarte, C. M., Fortes, M. D., Borum, J., Agawin, N. S. R., Bach, S., Thamapanya, U., Kamp-Nielsen, L., Kenworthy, W. J., Geertz-Hansen, O. and Vermaat, J., 1998. Changes in community structure and biomass of seagrass communities along gradients of siltation in SE Asia. *Estuarine and Coastal Shelf Science* **46:** 757–68.

van Katwijk, M. M. and Hermus, D. C. R., 2000. Effects of water dynamics on *Zostera marina*: transplantation experiments in the intertidal Dutch Wadden Sea. *Mar. Ecol. Prog. Ser.* **208:** 107–18.

Worcester, S. E., 1995. Effects of eelgrass beds on advection and turbulent mixing in low current and low shoot density environments. *Mar. Ecol. Prog. Ser.* **126:** 223–32.