Sustainable agro-fertilizers from marine plants in Pacific Small Island Developing States (SIDS)

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ABSTRACT

The effects of Climate Change are forcing farmers in Small Island Developing States (SIDS) to find novel methods to maintain crop productivity and sustainability. Past practices using chemical fertilizers and poor waste management severely damaged many coastal areas, leading to an ecosystem shift towards algal dominance. A proposed approach to deal with both the loss of crop productivity and the overabundance of seaweeds in SIDS, is to devise methods that divert excess marine plant biomass into agricultural uses through the conversion of the biomass to solid and liquid fertilizers. Seaweed-based fertilizers have already been tried with much success on crops in developed nations such as the United States and in European countries, but these are very expensive to import into Pacific Islands, and beyond the means of most farmers in the region. By empowering local farming communities with the knowledge to convert locally-available marine plant biomass into sustainable, ecologically friendly agricultural fertilizers, they would be able to make economies on the purchase commercial fertilizers which are detrimental to the environment, while at the same time reducing the spread of seaweeds on their coral reefs, and boosting the production of subsistence and cash crops which will improve their food and financial security.

INTRODUCTION

With the increasing effects of climate change being felt by Small Island Developing States (SIDS) in the Pacific Region, farmers are challenged to find ways to maintain crop productivity and sustainability with limited economic resources. Over the past decades, farmers were encouraged to use chemical fertilizers rich in phosphates and nitrates, before it was realized that these could cause long-term damage to the environment, freshwater table

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and marine ecosystems downstream by causing ecosystem shifts towards algal dominance (Kinsey & Davies, 1979). In the Pacific Islands, in recent years there has been concomitant issue with overabundant seaweeds, which are threatening to cause ecological shifts towards algae-dominated coral reefs with their associated losses in reef productivity, touristic attractiveness and fisheries livelihoods for local communities (Mosley & Aalbersberg, 2005).

Seaweed-based fertilizers have been used since the 1920's and earlier in Europe, but their use was restricted to coastal areas and was not cost-effective compared to their chemical counterparts. However, with the advent of liquid fertilizers and foliar sprays in the 1960's, there was renewed interest in the use of seaweed-derived additives in agriculture. In particular, a wide range of beneficial effects were noticed while using algal extracts, such as enhanced germination, better root development and growth, better assimilation of nitrogen and phosphorus, better resistance to pests and diseases, and cleaner, longer lasting fruits (Merigout, 2006; Kumar *et al*., 2012). For instance, brown seaweed concentrate applied as a foliar spray was reported to cause early fruit ripening, an increase in fresh fruit weight of up to 17% and an increase of about 10% in the number of harvested tomato fruits in trials done in South Africa (Crouch & Van Staden, 1992). Algal-derived hormones such as cytokinins are considered to produce these beneficial effects in terrestrial plants (Mooney & van Staden, 1986). However the current prices of imported seaweed liquid fertilizers is prohibitive for local Pacific communities. Increased water holding capacity and plant growth are seen with the addition of as little as 10% seaweed compost to soils (Eyras *et al*., 1998). In some countries such as Pakistan, drifted seaweed biomass is turned into organic compost through aerobic composting methods, and when applied to plants was found to have a germability factor comparable to that of cow dung and commercial fertilizers (Haq *et al*., 2011). Added benefits reported from the use of seaweed extracts as foliar spray on agricultural crops include a reduction in the number of harmful insects such as red spider mites (Hankins & Hockey, 1990), protection against oxidative and thermal stress in leafy vegetables such as spinach (Fan *et al*., 2011) and enhanced chlorophyll level in leaves leading to higher photosynthetic rates and growth (Blunden *et al*., 1997).

The increasing effects of global warming and human-induced pollution are rapidly changing the states of marine ecosystems, turning coral-dominated reefs in many places to seaweed-dominated reefs. These ecological phase shifts (Rohwer & Youle, 2010) reduce reef productivity and their ability to provide livelihoods to communities, while at the same time creating a nuisance through over-abundance and its associated problems (unsightliness, smell issues, fouling of beaches…). The natural solution to this problem, aside from rectifying it at the source, would be to find a sustainable outlet for this extra biomass, for instance as conversion to agricultural composts and solid/liquid fertilizers. The huge potential of marine plant biomass as agricultural additives being often overlooked, this chapter aims to develop, based on local case studies and original research, simple methods to empower coastal Pacific island communities to produce their own low-cost marine plant fertilizers which will improve their food security, economic situation and livelihoods.

THE USE OF MARINE BIOMASS AS FERTILIZER AND HEALTH PROMOTER IN LAND CROPS

The benefits derived from using seaweed-derived fertilizers include increased nutrient uptake, deeper root development, enhanced growth rates and increased resistance to diseases, pests and climatic stress (Kuwada *et al.*, 2006). In French Polynesia (Zubia, 2003; Zubia *et al*., 2003), an analysis of the invasive brown algae *Turbinaria ornata* and *Sargassum mangarevense* found them to be rich in potassium, nitrates, calcium, iron and polyunsaturated amino acids, with a very low level of any heavy metals. Antioxidant and antimicrobial properties were noted, while the addition of these brown algae as fertilizer improved the growth, dry weight and root development of maize plants. Similar benefits were reported by Merigout (2006) in an extensive study of algal chemical stimulants for plant growth. Tomato plants in general seem to respond well to seaweed fertilizer treatments. In South Africa, Crouch & Van Staden (1992) reported that a regime of soil drench and foliar spray of a concentrated extract of the brown alga *Ecklonia radiata* significantly improved growth and fruit production of tomato seedlings (early fruit ripening, 10% increase in fruit number and 17% increase in fruit weight) while Whapham *et al.* (1993) noted an increase in chlorophyll content for seaweed extract-treated tomato plants in the UK. In Argentina, green algae compost was again seen to be beneficial to tomato plants, improving growth soil water retention capacity and plant water stress resistance (Eyras *et al*., 1998). In another case of improved resistance, brown algal extracts were seen to promote natural defence responses in land plants by Klarzynski *et al.* (2000). The Mung Bean or Green Gram (*Vigna* spp.), an indian Subcontinent staple crop, was the subject of many studies involving seaweed-derived fertilizers (e.g. Kavipriya *et al*., 2011; Pramanick *et al*., 2013). The application of a 3% extract of the green seaweed *Caulerpa racemosa* was seen to elicit up to 74% more seed production in black gram (*Vigna mungo*) in trials in India (Sujatha & Vijayalakshmi, 2013) while the addition of 15% extracts of the red seaweed *Gracilaria* sp. to green gram (*Vigna radiata*) elicited a 33% increase in grain yield (Pramanick *et al*., 2013). Still in India (Kumar *et al*., 2012), the use of liquid seaweed fertilizer derived from the brown alga *Sargassum wrightii* at concentrations of 0.5 to 1.0% was found to elicit shoot and root growth in green gram plants, with significant differences noted according to the mode of delivery of the extract (root versus foliar). On the other hand, diluted extracts from the brown alga *Sargassum crassifolium* (which occurs in Fiji) were found to strongly inhibit germination of lettuce plants (Kuniyoshi, 1985) which highlights the importance of taxonomically screening various species of seaweeds with various crops for their suitability prior to releasing them as sources of land plant fertilizers.

Seaweed extracts as foliar sprays are also very beneficial as pest suppressants. For instance, in the UK red spider mites were significantly reduced on strawberry plants by application of a liquid extract of the brown seaweed *Ascophyllum nodosum* (Hankins & Hockey, 1990). In Chile, brown and red seaweed extracts (oligosaccharides) applied to tobacco plants were found to increase their size and improve their defenses against the tobacco mosaic virus (Laporte *et al*., 2007). During a recent visit to Dakuni Island in Beqa, it was noted that local farmers knew that the addition of the seagrass *Syringodium isoetifolium* to the base of tomato seedlings produced bigger, disease and pest-free plants with more fruits.

In addition to improving growth and resistance to disease and pests, brown seaweed extracts have also been found to stimulate the growth of Arbuscular Mycorrhizal fungi which enhance land plant growth by forming a symbiotic relationship with the host plant roots (Kuwada *et al.*, 2006). A further soil improving property of algal fertilizer is the ability to reduce leaching of nitrates, though improving soil aggregation and absorbing nitrates in an alginate matrix (Leach *et al.*, 1999).

SEAWEED CULTURE STUDIES

In Pacific SIDS, the two most abundant algae belong to the genera *Sargassum* and *Gracilaria*. To supplement natural stocks in view of large-scale use for conversion to fertilizer and biofuel, cultivation in an aquaculture setting is desirable. While *Sargassum*, a brown alga, is not readily cultivated, the red alga *Gracilaria* has been the subject of many studies and trials in the past, mainly due to its economic potential as a source of alginic acid and agar-agar. One of the most successful *Gracilaria* culture programs was conducted at Harbor Branch Oceanographic Institution at Fort Pearce, Florida (Hanisak, 1987). The species used was *Gracilaria tikvahiae* and was the focus of 10 years of research, including factors influencing growth, yields, and methods of cultivation. Under intensive culture conditions, the optimum stocking density was found to be 2 kg (wet wt.) m^{-2} with a final growth density of 2 – 4 kg m^{-2} (Lapointe & Ryther, 1978). Growth occurred at a temperature range of 12-36 °C with the optimum of 24-30 °C, at an optimum salinity of 24 - 36 psu. The alga had a high photosynthetic efficiency of 4% of the active radiation (Hanisak, 1987). Studies found that large turnover rates of seawater were required for the optimum growth of *G. tikvahiae*, and these were related to the prevention of elevated pH and associated limitations of carbon dioxide and bicarbonate (Lapointe & Ryther, 1978, Blakeslee 1986) while carbon dioxide enrichment significantly increased growth rates in batch cultures with no seawater exchange (DeBusk & Ryther, 1984). In tank cultures, the critical nitrogen concentration was found to be about 2% and identical when either nitrate or ammonia was the nitrogen source (Lapointe & Ryther, 1978). Recycled digester residues were shown to provide 62-83% recycling efficiency of the required nutrients for seaweed cultivation (Hanisak, 1981) and, when combined with existing nutrients, provided more than enough nutrients to sustain a high rate of growth.

The common overabundant algal species in Fiji, *Gracilaria edulis,* is commonly cultivated in Asia for agar production, notably in India where it occurs almost exclusively on the southern coastline (Raju & Thomas, 1971). The algae grow abundantly in undisturbed, clean waters just below the lowest tide level mark, attached to rocks and coral rubble. In times of heavy seas or storms, large pieces of algae get torn from their attachments and end up on beaches in large quantities, creating a foul smell and eyesore when decomposing. The seaweed can regenerate very quickly from vegetative fragments of any parts of the plant, explaining its ability to spread and colonise new suitable habitats at a fast pace. Trials at growing *Gracilaria edulis* on coir-rope lines off the coast of Krusadai Island in Southern India (Raju & Thomas, 1971) yielded up to 3.5 kg of fresh material per meter of coir rope per year. Similarly, Siraimeetan & Selvaraj (1999) grew the alga on long line coir ropes in the open sea (1 m depth) off the Tuticorin coast in India, with a 16.1 fold increase in biomass after 74 days. While cage and tank cultures grew very slowly and were heavily epiphytized, the open sea coir raft (4 m^2 with a 10 cm mesh size and 2.5 cm rope thickness) gave rapid and healthy harvestable yields when seeded with 2.5 kg of 5 cm lengths of algae. In the latter experiment a growth rate of 4.3 mm per day was achieved, with a biomass yield of about 10 kg per m^2.

Also in India, Jayasankar & Varghese (2002) cultured *G. edulis* on 25 m^2 floating nylon rope rafts in the open sea (5 m depth) and reported harvestable yield after 76 days of growth. This experiment was done in conjunction with mussel farming, and no additional nutrients were provided. The authors highlighted the fact that seawater temperature and salinity play an important role in *G. edulis* growth and survival rates.

In tropical Brazil, Bezerra & Marinho-Soriano (2010) experimented with rope cultivation of the related species *Gracilaria birdiae*, reporting a mean growth rate of 4.4% per day and a mean biomass value of 3.61 kg per m^2. They highlighted the great potential of that species for economic mariculture.

More recently in India, Ganesan *et al*. (2011) cultivated *Gracilaria edulis* using floating rafts, and reported obtaining a higher biomass than other methods, with 12.5 kg per m^2 and a mean growth rate of 7.4% per day. Biomass values were found to be 184% higher and growth rates 2% higher in subtidal cultures rafts than in near-shore ones. The alga was cultivated successfully for 8 months per year, with maximum growth rates in subtidal areas at seawater temperatures of 24-28°C and low turbidity. Optimum harvest time was after 60 days, and periodic weeding of epiphytes was seen to be beneficial to improving yield.

Considering past studies, the most suitable candidate algal species for cultivation for Pacific SIDS in view of production of biofertilizer would be *Gracilaria edulis*, which is readily available on some of the larger islands such as Fiji, and have a high growth and turnover rates. *Gracilaria* has also the highest yield of biomethane under anaerobic digestion (Table 1).

ANAEROBIC DIGESTION STUDIES INVOLVING MACROALGAE

The production of biomethane by anaerobic digestion is a three-step process that occurs widely in nature within environments such as ocean and lake sediments, marshes, and the digestive tracts of animal, and first involves the biological conversion of the organic components of biomass into simple products such as acetate, carbon dioxide, and hydrogen by a mixed population of decomposing bacteria (Fig. 1). A second set of acidic bacteria then converts these soluble compounds into organic acids, which are then utilized by a mixed population of methanogenic bacteria to produce methane (60%) and carbon dioxide (40%) with trace amounts of hydrogen sulfide and other gases, at an optimum temperature range of 37°C (mesophylic bacteria) to 54°C (thermophylic bacteria). Thermophylic digestion is less stable, but gives up to 20% more yield than the colder mesophylic conversion (Gunaseelan, 1997; Chynoweth, 2002; Brown & Caldwell, 2008). The overall chemical reaction can be summarized as follows:

$$C_6H_{10}O_5 + H_20 \longrightarrow 3CO_2 + 3CH_4$$

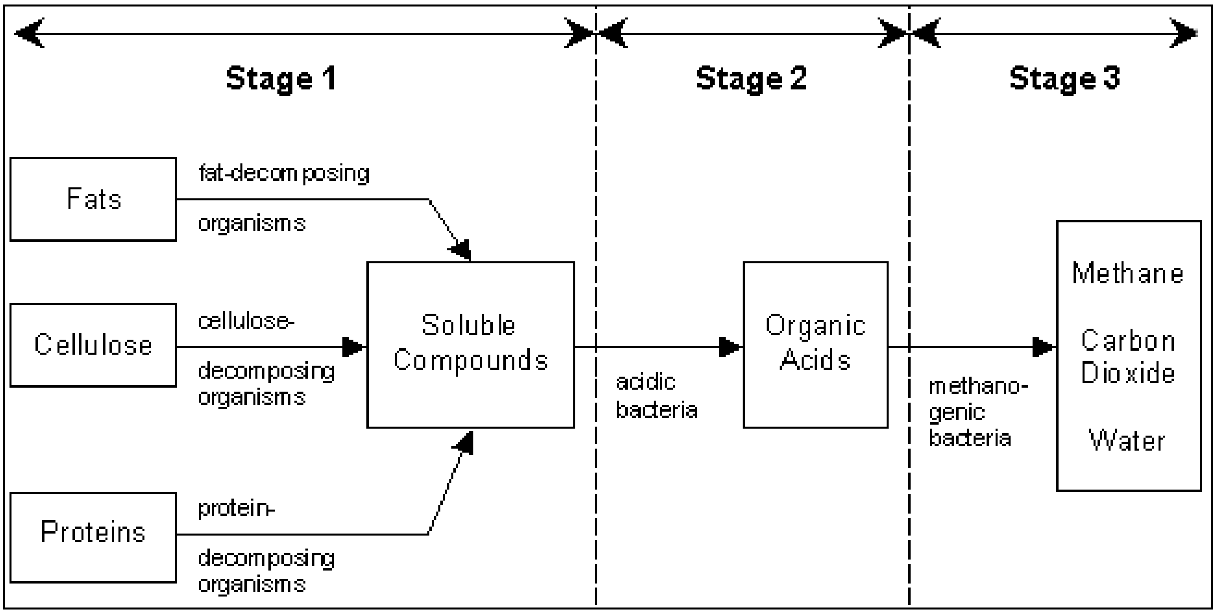

Figure 1: The three stages of anaerobic digestion involving three sets of specialized bacteria (Source: Encyclopedia of Alternative Energy www.daviddarling.info/encyclopedia/A/AE_anaerobic_digestion.html)

For example, natural gas is a fossil fuel resulting from the anaerobic decomposition by bacteria of organic matter millions of years ago, when the pre-photosynthesis atmosphere lacked the oxygen we breathe today. The anaerobic digestion of algae has been demonstrated with high conversion rates and yields, using preferably one or two phase digesters with longer solids than hydraulic retention times. Because algae grow in a salty environment, the bacteria used in the digestion process must be adapted to a halophylic medium and are best obtained from anaerobic marine sediments or fish guts. Marine algae have high growth rates and can propagate very quickly in the presence of abundant nutrients. The photosynthetic efficiency of aquatic biomass such as algae is on average 6% higher than that of terrestrial biomass (Aresta *et al.*, 2005) and the red macroalgal genus *Gracilaria* has one of the highest methane yields once digested (0.31 m^3 kg^{-1}; Roesijadi *et al.*, 2010). In general, brown algae such as kelps (*Macrocystis* spp., *Laminaria* spp.) and *Sargassum* spp. have a lower methane yield but are the easiest to digest, while red algae such as *Gracilaria* spp. have higher yields but are the most difficult to process (Table 1). While it has been demonstrated that digestion to methane can occur with macroalgae, a lot of research is still needed to fine-tune the process. In particular, for large-scale production, the performance of the anaerobic digestion process at normal tropical ocean temperatures needs to be improved, efficient bacteria need to be screened, selective breeding and expanded culture studies need to be carried out, and digesters have to be designed specifically for macroalgae (Stanley, 2009). Macroalgae have a promising future for biofuel production, due to their higher yield rate and absence of inhibiting lignocellulose compared to terrestrial plants (Sikes *et al*., 2011).

Species	**Methane yield (dm^3 CH$_4$ $^{g-1}$ VS$_{add}$)**
Gracilaria spp.	0.25 – 0.40 [1, 2]
Ulva spp.	0.22 – 0.33 [2, 3]
Sargassum spp.	0.12 – 0.19 [1]

Sources: [1] Bird *et al*. (1990); [2] Roesijadi *et al*. 2010 ; [3] Migliore *et al*. 2012.

Table 1: Schematic of a typical domestic anaerobic digester for biomass designed in the context of renewable energy projects in Pacific Islands such as Tuvalu and Fiji.

In the early 1970's, encouraged by the oil embargo and energy shortages, the U.S. Navy as part of the Biomass Program experimented with large-scale offshore cultivation of kelp (*Macrocystis pyrifera*) off the California coast, and successful demonstration was done of the conversion of algal biomass to methane via anaerobic digestion (Chynoweth, 2002). However, the project was not successful for a number of logistical reasons and terminated in the late 1970's, coinciding with a decrease in world oil prices and subsequent disinterest in alternative energy sources. The main problems hindering the projects were a lesser growth rate in cultured plants than in the wild, poor attachment and dislodging of the large kelps from the culture platform, and the eventual destruction of the platform by a heavy storm which led to the withdrawal of federal funding, putting an end to the program.

More recently, annoying blooms of the green alga *Ulva* in Japan led to the setup of a pilot seaweed to methane conversion plant (Matsui *et al*., 2006) using both *Ulva* and the brown alga *Laminaria*. Successful anaerobic digestion of the biomass to about 60% methane and 40% CO_2 was obtained, with a higher yield for the brown alga *Laminaria* (22 m^3 CH_4 T^{-1}) than for the green alga *Ulva* (17 m^3 CH_4 T^{-1}). The two-step digester design used a 5 kl pre-fermentation tank, a 30 kl methane fermentation tank, and a 30 kl inflatable gas holder. Bacteria were retained in the fermentation tank by using porous matrices. Hydrogen sulphide residues in the biogas were removed by ferrous oxide, and the sludge residue used as fertilizer for spinach crops. The resulting biogas, mixed with city gas, powered a 9.8 kW electrical generator and supplied 22.7 kW of heat transferred back to the fermentation tanks (25-35°C for the pre-fermentation, and 55°C for the methane fermentation). The optimum pH level was found to be 7.5, with a more stable digestion for the green alga. Waste milk was added to the fermentation mixture when the input of seaweed was low. While the concept of the latter study was good, in practice the experiment was uneconomical because of the very high cost of extracting useful by-products from the algae prior to methane fermentation, leading to a revised concept by Yokoyama *et al*. (2007) that focussed only on the generation of biogas and the use of digestion by-products as agricultural fertilizer. An annual energy production of 1.02×10^9 kWh yr^{-1} was estimated in that study, with a total CO_2 mitigation of 1.04×10^6 tonnes per annum for nine sites in northern Japan. The authors recommended further research in more efficient methane fermentation methods as well as rapid seaweed growth and drying techniques for the chosen Japanese species (*Laminaria japonica*).

In a similar but smaller-scale experiment in Chile, Vergara-Fernández *et al*. (2008) evaluated a two-stage anaerobic reactor system consisting of an anaerobic sequencing batch reactor (ASBR) and an upflow anaerobic filter (UAF) to digest the large brown algae *Macrocystis pyrifera* and *Durvillea Antarctica*. Since the authors washed the alga first, non-halophilic bacteria found in cow manure were used in the fermenters. This study found that the methanogenic phase is the limiting factor in the anaerobic digestion of macroalgae, with 70% of the biogas being produced in the UAF. A biogas production of 180 L kg dry algae $^{-1}$ day $^{-1}$ was achieved, with methane concentration near 65%.

While all of the above studies required prior washing and drying of the biomass in freshwater before being digested, Migliore *et al*. (2012) recently investigated a method that can digest green and red algal biomass directly from seawater, using naturally occurring bacteria obtained from marine sediments of an Italian lagoon. Methane yields of up to 380 dm^3 kg^{-1} were obtained, and a good yield of biogas was shown to be heavily dependent on the presence of suitable bacteria-containing sediments.

More recently, as part of a renewable energy project being carried out by the authors and colleagues at the Pacific Centre for Environment and Sustainable Development of the University of the South Pacific in small island nations such as Fiji, Vanuatu and Tuvalu, a low-cost anaerobic digester design (Fig. 2) was developed for use at the community household level. This design is versatile, and can use both marine and terrestrial biomass, with the digestate by-product being suitable for direct use as an agricultural fertilizer. A recent grant will enable more research into optimum mixtures of feedstock and bacterial inoculate to maximise yields.

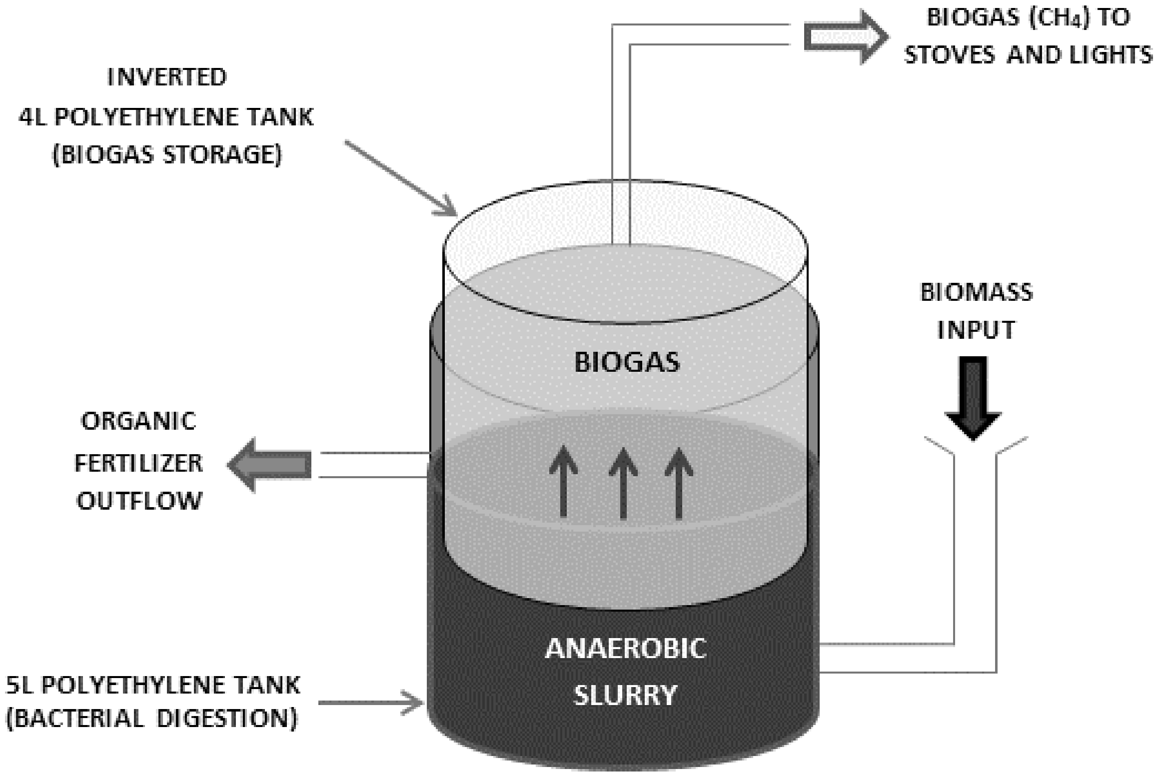

Figure 2: Schematic of a typical domestic anaerobic digester for biomass designed in the context of renewable energy projects in Pacific Islands such as Tuvalu and Fiji.

OCEAN MACROALGAL AFFORESTATION FOR SIDS

The process of Ocean Macroalgal Afforestation (OMA), which is an ocean-based sun-algae-biomethane producing process, provides a sustainable new source of renewable energy and low-cost, highly effective agricultural fertilizer as a by-product that has the potential to improve the local economy, create employment, reduce food and fossil fuel imports, reduce greenhouse gas emissions, increase ocean species biodiversity, clean up excess nutrients from sewage treatment plant discharges, and clean up beaches fouled by seaweed (N'Yeurt *et al.*, 2012). Figure 3 summarizes the concept of the long-term open-ocean process. The process provides multiple products simultaneously: energy from biogas natural biogas (~60% biomethane which is directly usable for cooking and lighting), seafood, fertilizer, plus the recyclable nutrients remaining after anaerobic digestion. It is an approach to sustainable development that is appropriate for island and coastal communities worldwide.

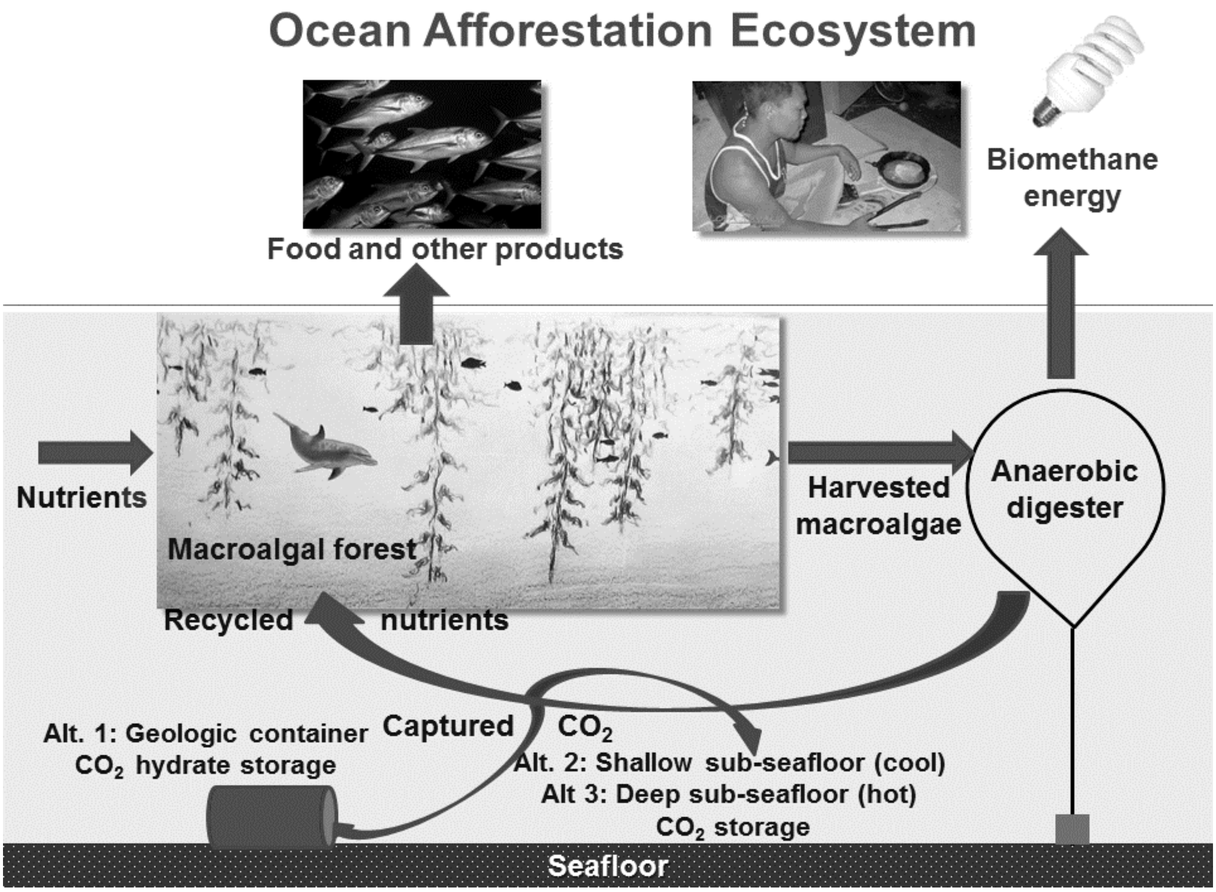

Figure 3. The OMA Integrated Multi-Trophic Aquaculture concept (adapted from N'Yeurt *et al*., 2012)

The nutrient by-products of the OMA process are used to sustain the production of more biomass, as well as fish and marine life, increasing biodiversity and boosting fisheries. The most practical way to mitigate CO_2 emissions is seen to be by increasing photosynthesis activity through photosynthesis in both standing tree biomass and ocean primary producers such as macroalgae (Ritschard, 1992). The removal of CO_2 by seaweeds has been shown to be an important component of the Blue Carbon cycle in the world's oceans (Nellemann *et al.* 2009), removing about 10 ton CO_2 per hectare per year in preliminary trials in Asia (Division of Earth Environmental System, 2009).

So far in Pacific SIDS such as Fiji, biofuels experiments have been concerned with extracts from copra and starchy crops such as cassava, for the production of biodiesel and ethanol (Cloin, 2007; Krishna *et al*., 2009). There has not been any work done on Fiji's algal biomass. However, other countries such as Italy and Chile have in place research programs for producing biogas and fertilizer from the anaerobic digestion of macroalgae (Vergata-Fernández *et al*., 2005, Migliore *et al*., 2012). Importantly, marine algae do not compete for agricultural land space, food crop production or fresh water and can be grown with relatively less maintenance in a wide range of coastal and oceanic waters.

Of several seaweed species screened in the past for culture studies, the red alga *Gracilaria tikvahiae* showed the highest yield of 127 dry tons per hectare per year, at an optimum seawater temperature of 24-30°C and growth density of 2-4 kg m^{-2} (Hanisak in Chynoweth, 2002). In Fiji, an equivalent, non-commercial species of *Gracilaria* (*G. edulis*) is commonly found washed up on the coastline in great quantity in several sites on Viti Levu (Fig. 4), and could be easily cultivated for OMA purposes. This particular Fijian species does not seem to have a good quality agar content for the usual commercial purposes (T. Pickering, pers. com.) but has good properties for some specialized pharmaceutical uses (P. Kumar, pers. com). It is highly likely that large natural beds of this alga exist in the near subtidal within the Suva lagoon, and get periodically uprooted and washed up during episodes of rough seas linked to windy conditions. The decaying masses of this seaweed create a recurrent smell problem, notably in the Nasese area of Suva and Viseisei Village near Nadi (pers. obs).

A 500 ha aquaculture operation could in theory produce about 7,000 dry tons of algal biomass per year. This biomass may be converted to biomethane, powering continuous 800 kW electricity generation (worth about $1.5 million USD per year) plus 1,500 kW of useable heat that could be used for a variety of purposes, such as heating the anaerobic digesters (N'Yeurt *et al*., 2012). In addition to biofuel, residue sludge from the anaerobic digestion would have a high content of potassium, reportedly up to 13.49% dry weight for *Gracilaria edulis* (Mageswaran & Sivasubramaniam, 1984), plus nitrates and other minerals. This residue could be washed, dried and crushed to be recycled to fertilize the seaweed farm, or be sold or used by the local communities as a valuable crop fertilizer, hence eliminating the need and problems associated with the use of chemical fertilizers on coastal farms (Hanisak, 1981, 1987). *Gracilaria edulis* also has one of the highest content of protein and nitrogen (idem; Jayasankar & Paliwal, 2002) with potential applications as food additives for plants and livestock. Some experiments to convert algal biomass into biofuel and fertilizer are currently underway in the Ortebello Lagoon, Italy (Migliore *et al*., 2012) but no reciprocal studies exist at the moment in the Pacific region.

Figure 4: *Gracilaria edulis* washed up on the Nasese foreshore, Fiji, June 2012

BACKGROUND IN SIDS

In the Fiji Islands and Tuvalu, marine algal blooms have become an increasing issue over the last few years, as is increasingly the case worldwide (Conley *et al*. 2009; Leliaert *et al.*, 2009; Liu *et al*., 2013). Large outbreaks of the red alga *Gracilaria edulis* have been reported washing up on beaches of the main island of Viti Levu, Fiji (Burese, 2013), while in Tuvalu, the local population has been confronted since 2011 by the sudden appearance of a large swath of the brown alga *Sargassum polycystum* forming a literal belt from the shoreline to about 100 metres out into the lagoon (N'Yeurt & Iese, unpubl.). Based on anecdotal and research-based evidence, similar outbreaks have been reported from other islands in the Pacific. There appears to be a clear link between overpopulation, periods of drought, increased water temperature, poor water circulation and outbreaks of these algae. Both climate change and development aspects seem to be the cause, with specific conditions particular to each locality being affected by this phenomenon. Main causes include inputs of Phosphates and Nitrates into coastal areas from agricultural activities (Conley *et al*., 2009) and washed down wastes from animal husbandry such as cattle, pigs and chickens (Liu *et al*., 2013).

While there is a definite link between the use of algal compounds such as alginates and improved growth of land plant crops (Kay, 2004; Kumar *et al*., 2012), few farmers to date make use of marine plant fertilizers, especially in Pacific Islands. In rural farming communities of Beqa Island, Fiji, the marine seagrass *Syringodium isoetifolium* has been used for several years with positive results on tomato, water melon, kava (*Piper methysticum*) and dalo (*Colocasia esculenta*) crops (N'Yeurt & Iese, pers. obs.). In that particular instance, the knowledge was transferred by one of the village members who had visited Israel in the Middle East, and observed such practices there. Non-Governmental Organisations like Australia-based Organic Matters Foundation offer Pacific island farmers with alternative ways to mainstream agricultural practices and inputs of chemical fertilizers, and have been conducting 'soil schools' in remote areas of Fiji such as Taveuni Island; their methods also include using seaweed to augment soil qualities. In the small atoll nation of Tuvalu, a couple of farmers have been recently experimenting independently using the invasive brown alga *Sargassum polycystum* on their home gardens, with good success (Iese, pers. obs.). The situation on such small atolls is particularly critical, because the inherent porosity of the soil makes for poor retention of chemical fertilizers, which tend to get easily washed out into the lagoons, compounding the over-abundant seaweed issues they have been facing for the past few years.

Hence the current situation in Pacific Islands concerning the use of seaweed fertilizers is at best anecdotal and scattered in both time and space, with no widespread knowledge about such practices. Most farmers still turn to mainstream practices using phosphate and nitrate-based chemical fertilizers when it comes to improving the quality of their plantations and home gardens. In order to bring together all stakeholders involved in the process of sustainably using marine-based agro-fertilizers, internet-based tools such as the United Nations-sponsored Pacific Solution Exchange Network can act as sharing fora for questions related to these issues. In May 2013, the first author initiated such a question on the PSE network titled 'Solutions for Overly Abundant Seaweed', which generated considerable interest in the Pacific region, and provided much of the insight used in this chapter to find local solutions tailored to the SIDS Pacific context.

CASE STUDIES OF OVERABUNDANT SEAWEEDS IN PACIFIC SIDS

Case study I: Viseisei Village, Fiji

Viseisei Village (Fig. 5) is located about 10 km north of Nadi on the main island of Viti Levu, Fiji. It is home to about 800 people and is the legendary point of 'first landing' of the i-Taukei people about 3,500 years ago. The village is within the Lautoka-Nadi corridor, which hosts a large number of tourist resorts as well as the Vuda oil terminal, Fiji's largest. The closest freshwater effluent is from the Vuda River immediately south of the village, which draws from a catchment in the Sabeto / Mount Evans hills. There are a number of farming communities with cattle farms, as well as a large piggery upstream.

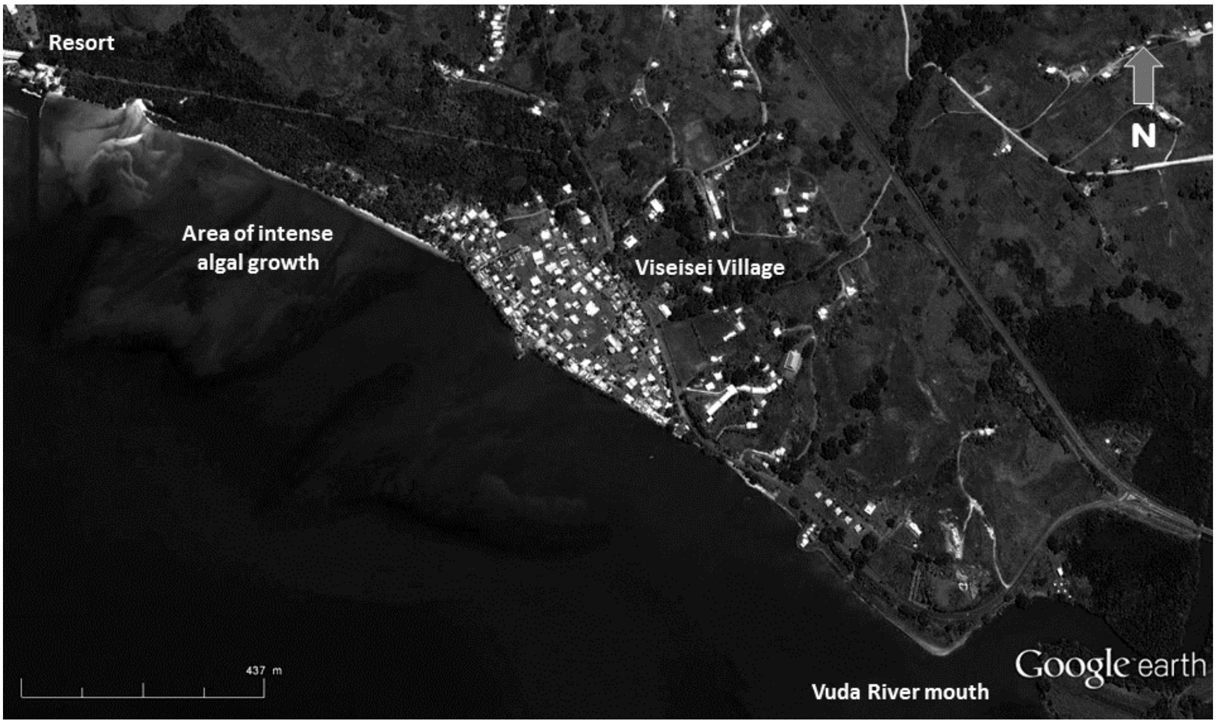

Figure 5. General situation of Viseisei Village, Fiji.

In December 2011, the University of the South Pacific's Center for Environment and Sustainable Development (PaCE-SD) was contacted by the Viseisei community about a recent and novel seaweed bloom environmental and problem. The notable effects were a large quantity of seaweed being continually washed ashore on the beaches adjacent to the village, generating a foul smell and eyesore as they decomposed. Also, the reef flats in front of the village were covered with algae and the fishing grounds altered, with villagers having to travel long distances by boat to catch fish and other marine products for their livelihoods. In response to this request, a team of four people lead by the first author was sent to Viseisei Village in early March 2012.

A rapid survey of the environmental situation at the village and its surrounding revealed a definite issue with overabundant algae, which littered the beaches between the main village and a resort further up north on the coast (Fig. 6). Seawater samples were also taken for analysis of nitrate, phosphate and ammonia in order to monitor pollution levels in the village's foreshore area. The results of these analyses showed levels of Nitrates between 0.05 and 0.25 mg/L, while sewage-derived fecal coliform levels were very high at all sites. Even though these readings were mostly within or above the guideline of 0.062 mg/L for polluted waters in Fiji proposed by Mosley & Aalbersberg (2005), because the samples were taken within the algal beds themselves, these readings could be well below the actual amounts of Nitrates being inputting the ecosystem since these elements can be absorbed almost immediately by the algae which act effectively as highly efficient nutrient sinks. Two possibilities were suggested for the origin of the nutrients: a tourist resort immediately to the northwest that was known to regularly (albeit surreptitiously) discharge sewage effluents into the lagoon, and farming communities upstream along the Vuda River whose mouth discharges to the south of the village (Fig. 5). It was understood from local residents that a number of cattle farms were upstream on the Vuda River, as well as a large-scale piggery on a hill. While the piggery was not immediately on the banks of the river, it could be postulated that at times runoffs of pig waste could find their way to the flowing water and deposit them to the Viseisei coastline. Likewise, cattle wastes as well as fertilizer runoffs from the farms on the river banks could add to the nutrient load of the Vuda River. Both the inputs of nutrients from the resort and the Vuda River could be confluent on the Viseisei coastline, contributing to the area of intense algal growth which was observed. While the patch of algal growth was quite delimited on the reef flats, in most places algal cover was 100% and monospecific, composed of the red alga *Gracilaria edulis* (S. G. Gmelin) P. C. Silva. This is a common Indo-Pacific species, cultivated in other parts of the world such as India (Siraimeetan & Selvaraj, 1999; Ganesan *et al*., 2011).

The outcome from this exercise highlighted the fact that a clear link cannot be always made between overabundant seaweed growth and levels of nutrients at the sites themselves; in most cases one has to look further upstream or inland for the causes. It is anticipated that though a recently-funded project at the University of the South Pacific in Fiji, workshops on the use of marine organic fertilizers will be run at Viseisei village to offer the local community a symptomatic solution to their overabundant algae issue, at the same time improving their food security and providing an additional and alternative source of income.

Figure 6. Beach at Viseisei Village, showing seaweeds washed ashore. Inset: *Gracilaria edulis*.

Case study II: Beqa Island, Fiji

The island of Beqa (Fig. 7) lies 7.5 kilometers to the south of Navua on the main island of Viti Levu, Fiji. The island has a land area of 36 square kilometers and has a maximum altitude of 480 meters; geologically it is a stratovolcano formed about 5 million years ago. There are 9 villages on the island, Dakuibeqa (the chiefly village of the Sawau people), Dakuni, Soliyaga and Rukua are noted for the tradition of fire-walking. The population of Beqa in 2006 was about 1,300 with the main source of income being tourism. All the villages are found along the coast, and have access to water. Transport to the mainland is by boat. Much of the young people on the island are either occupied by agriculture, or work on the mainland (Navua or Suva) and return often to the island owing to its proximity. Beqa is noted for its fertile volcanic soils, and is the only island in Fiji producing off-season tomatoes which are sold in markets in Navua and Suva. Other crops include taro, kava, eggplant, bananas and watermelons. The terrestrial and marine fauna is very diverse and the latter provides a bulk of the food source for islanders. One of the biggest threats to the environment on the island comes from the indiscriminate disposal of garbage on the beaches, especially batteries, as there is no organized trash disposal system.

Figure 7. Situation map of Beqa Island, Fiji and the southern village of Dakuni. Inset: Dakuni Village Bay with hillside plantations of tomato, cassava, banana and kava in the foreground.

Dakuni Village is located on the southeast of Beqa Island (Fig. 7), and consists of a number of households around a church and community hall. The coastal area of the village is narrow, secured by a seawall, with some land reclamation, while a steep hill juts out directly behind the village. This makes the village particularly vulnerable to natural disasters such as tsunamis and storm surges. Some backyard plantations are found behind the village, while others are found a bit further inland and uphill, while the main plantations are found in the interior of the island. Some households have solar panels as part of a Government rural electrification scheme. A preliminary rapid assessment of the crop diversity and management in Dakuni Village was carried out by two teams from PaCE-SD of the University of the South Pacific in March 2012. Investigations were done on the agriculture and food security aspects of the village, and also the marine environment and possible inter-linkages between the two. A total of 19 crops including both tree crops and short lived vegetables were sighted during the field work, spread in three different types of garden plots.

Main crops grown at Dakuni Village in Beqa include kava or yaqona (*Piper mysticum*), tomatoes, slippery cabbage (*Abelmoschus manihot*), Cassava (*Manihot esculenta*), Eggplant (*Solanum melongena*), Banana (*Musa* spp.), Watermelon (*Citrullus lanatus*) and Pineapple (*Ananas comosus*). The first type of garden plots are of the small backyard type and consist of mostly intercropped crops of egg plants, slippery cabbage, yam, sweet potatoes, sugar cane, and cassava. They are important sources of food supply that can be easily accessed during extreme weather conditions and are also used as nurseries or seed/planting material storage banks. The second types of gardens are within walking distant from the village and of larger size and cultivated density. This type of garden, mostly consisting of tomatoes, watermelons and kava is mostly used for commercial purposes and is an important source of income to farmers. The third types of gardens are located much further from the village in the fertile interior of the island and include taro and kava.

The steep landscapes of Beqa Island and continuous cultivation of the steep hills lead to a reduction of yield of important food security and livelihood crops. This is due to the loss of important nutrients in the soil. Climate extreme events such as heavy rainfall and frequent cyclones exacerbate soil nutrient erosion and reduction of yield. Dakuni farmers manage their crops using three major techniques: intercropping, crop rotation and fallow, and the use of seagrass and algae manure (*Syringodium isoetifolium; Sargassum polycystum*) applied at regular intervals to their crops (Fig. 8). Reported benefits of using seagrass were rapid growth, early and longer fruiting season (e.g. for tomatoes), healthier plants less susceptible to pests and diseases. The increased yield of tomatoes linked to the use of marine plant manure leads in turn to an increase in revenue collected; also Dakuni farmers are the only ones reported to be able to grow tomatoes during the off-season period. While yet unproven, their use of natural marine fertilizers, in conjunction with the local micro-climate, may contribute to this phenomenon of off-season fruiting. Currently the collection of seagrass and algae for fertilizer is only dependent on material washed up on beaches during the tides or storms; this practice was apparently shown to them by a villager who had witnessed the use of marine plant fertilizers while visiting Israel in the Middle East.

Figure 8. Marine plant fertilizer (seagrass, *Syringodium isoetifolium*: inset) applied to the base of a tomato plant in Dakuni Village, Beqa.

It is recommended for the community to continue using such marine-derived fertilizer in a sustainable manner, and we hope to further refine and improve these techniques for the communities in future through our own research at USP in conjunction with other island communities in the region, especially in such areas as composting and liquid fertilizers which will ensure a long-term supply of manure, as well as surplus which could become a source of income. The installation of domestic biomass digesters supplemented with marine algae and seagrass could also provide a sustainable source of cooking and lighting biofuel.

Case Study III: Funafuti, Tuvalu.

Tuvalu is a small atoll nation of 26 km^2 land area in the central South Pacific consisting of three reef islands and six atolls, located half way between Hawaii and Australia, with a total population of 10,837 persons in 2012 (Government of Tuvalu, 2012) mostly living on the main island of Fongafale. Owing to its low profile with the highest point only 4.6 metres above sea level, it is very prone to the effects of climate change, especially rising sea levels. During spring tides much of the atoll is inundated by seawater, with the freshwater lens and little available arable land contaminated by salt, making agriculture a real challenge, if not an impossibility in many cases. Because of the porosity of the sandy soil, nutrients leach out very quickly and it forms a poor basis for growing crops; farmers have relied heavily on imported phosphate-based fertilizer to augment the soil qualities. It is a national challenge for Tuvalu to increase the fertility of the soil, enhance subsistence agriculture as well as household income from the sale of garden produce. The traditional crops in Tuvalu are giant Swamp taro (*Cyrtosperma chamissonis*, local name 'Pulaka'), bananas, breadfruit and sweet potatoes. Home gardening is characterized by groves of coconut trees with inter-planting of crops, and the use of special pits filled with organic matter wastes to create soil for the cultivation of swamp taro and giant Swamp taro. While such family-owned pits make it easier for the plants to access the freshwater lens, rising sea levels and stronger king tides make salt intrusion into the water lens a problem, necessitating relocation to higher ground which simply does not exist in most cases.

In 2011, there was an episode of severe drought on the island, following which there were reports of a sudden bloom of algae forming a dense belt on the lagoon side of the atoll adjacent to populated areas (Fig. 9). Initially the proliferating algae consisted of a filamentous type (possibly *Moorea majuscula*, a cyanobacteria) which was then replaced almost exclusively by the large brown alga *Sargassum polycystum*, attaining wet biomass values of up to 3.5 kg m^{-2} (N'Yeurt & Iese, unpubl.). The plants grow in a belt from the shoreline to about 100 metres offshore on the lagoon side of the atoll, with their distribution strongly linked to sources of anthropogenic nutrients (latrines, domestic wastes) and animal farms (piggeries, poultry sheds). The amount of algae is such that it causes real problems to the local communities, though loss of fishing grounds, hindrance to shipping (the algae can each up to 2 metres long and get caught in boat propellers) as well as washing up on the beaches creating a foul smell and eyesore as they decompose in the humid equatorial heat.

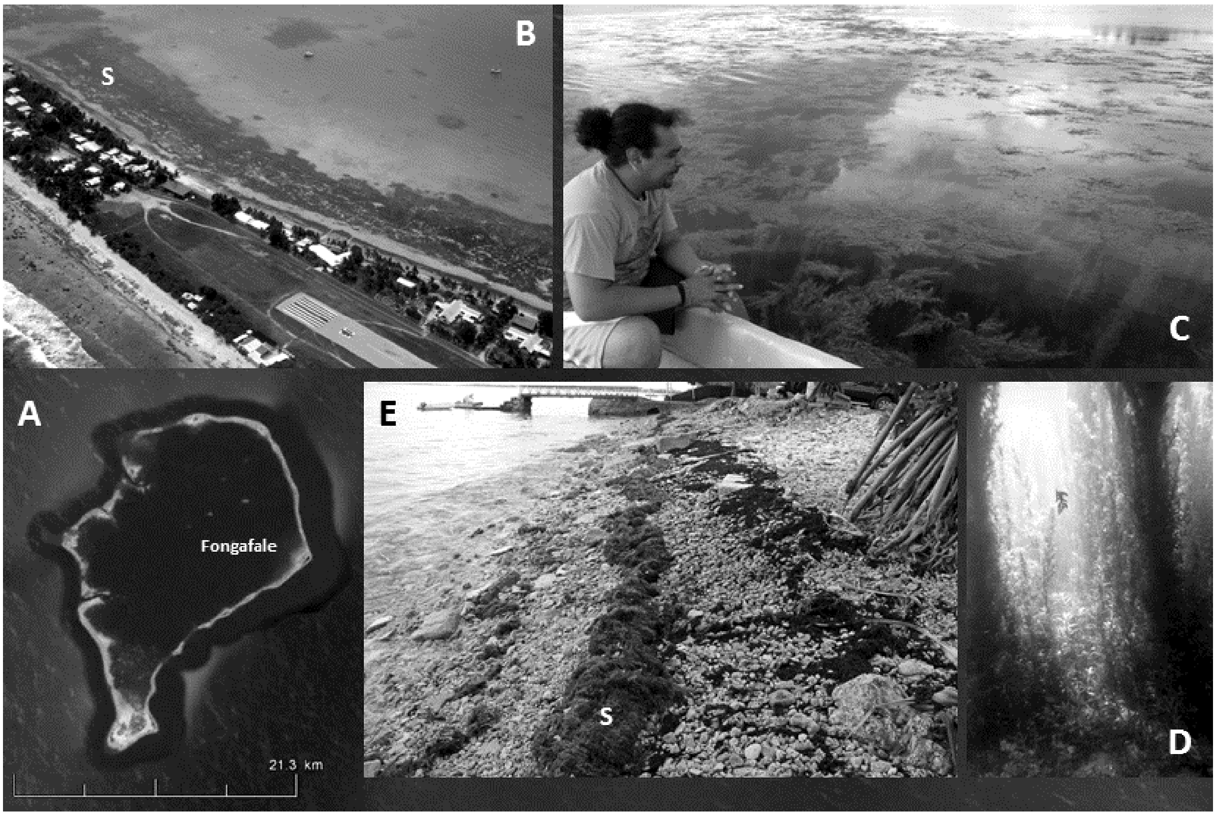

Figure 9. Algal bloom in Funafuti atoll, Tuvalu. A: Situation of Fongafale Atoll in Tuvalu. B: the *Sargassum* seaweed belt (S) seen from the air. C: Area of the lagoon of Fongafale infested with *Sargassum*. D: Inside the *Sargassum* beds, with plants attaining heights of up to 2 metres. E: *Sargassum* (S) being washed up on the beaches of Fongafale atoll.

Ten home garden farms were visited at Funafuti atoll on Tuvalu by the second author in November 2013, as part of a visit by both authors to investigate the seaweed bloom issue on the low-lying island. The main purposes of the visits were to observe the type of crops cultivated by the farmers, how they plant their crops and also to conduct interviews on whether they would adopt seaweed fertilizer as an organic compost. Five farmers were interviewed. It was very encouraging to see that home garden farmers in Tuvalu are planting various crops including but not limited to pawpaw, bananas, cucumber, eggplant, water melon, spring onions, chili, Chinese cabbage, pineapple, sweet corn, long beans, tomatoes, guava, lime, avocado, taro and new varieties of giant swamp taro. Most of the farmers obtained their seeds, or planting materials from the Taiwan Technical Mission (ICDF). The Taiwanese Technical Mission has a Horticultural Crop Development Project in Funafuti close to the airport, designed to "assist with and demonstrate technologies associated with vegetable and fruit cultivation and production as part of a wider promotion of the consumption of fruits and vegetables". Some farmers are now starting to produce their own seedlings; all farmers started home gardening to provide healthy fresh foods for their households, source of income, alternative exercise, and also to participate in regular farmers' competitions held by the Agriculture Department and Taiwan Technical Mission (TTM).

Most of the farmers visited used inorganic fertilizers provided by the TTM but after they heard of the negative impacts of inorganic fertilizers on coastal water especially in atolls, they are shifting back to organic farming using compost (they bought from waste management or they collected themselves) and animal manures. Two farmers interviewed mentioned that they used or were using the seaweed *Sargassum polycystum* as an organic fertilizer. Mr. Otinielu Tausi soaked his seaweeds for three days (three times in three days) before mixing with composts. Mr. Tausi tried mixing compost with seaweed before but he did not notice any difference in growth compared to other non-seaweed fertilized crops. He mentioned though that he did not spend more time observing his crop growth so therefore his conclusions could be unfounded. However, he was very eager to use seaweed again after our discussions.

Another farmer Mr. Amasia Amitai, was using *Sargassum polycystum* which he collected washed up on beaches to use on his various crops which included tomatoes, cabbage, watermelons and long bean (Fig. 10). He soaked his seaweed in water before application and also reused the same water for application on his plants. He had been using this method for a period of six months and reported good growth results to date. The washed, dried seaweed is manually applied to the base of the plants at regular intervals (Fig. 10D). This farmer observed a fast growth of cucumber and watermelons that are fertilized with seaweed compared to other farmers who are not using seaweed and planted their crops during the same period. This successful farmer is sharing this knowledge with his close friends and neighbors and they are all eager to use seaweed as fertilizers.

Figure 10. Using algal fertilizer on crops in Funafuti atoll, Tuvalu. A: Tomato farming plot of Mr. Amasia Amitai. B: A tomato plant with *Sargassum* seaweed (S) applied around the base.

C: A mature tomato from a seaweed-fertilised plant. D: Mr. Amitai applying seaweed fertilizer. E: Buckets of collected *Sargassum* prior to application on tomato plants.

SOLUTIONS AND RECOMMENDATIONS

In order to address the issue of overabundant seaweeds in Pacific SIDS and at the same time provide an alternative livelihood and food security for local communities, we recommend that solutions need to be tailored to the Pacific context, using locally available materials and require minimal financial investment. Local Non-Governmental Organizations in the Pacific need to be involved to assist communities with the best practice methods that can be used. There needs to be a continuation of current studies on the effectiveness of marine plant fertilizers on agricultural crops, based on seasonality, types of plants, and the potential to mix marine biomass with other sources such as garden refuse, human and animal manure, and animal by-products and carcasses. There is also a need to document and share best practices on controlling these algae as well as turning them to useful and sustainable products as biogas, fertilizers and animal feeds. These best practices should be well distributed and simplified in order for communities to replicate then and improve them effectively to suit their conditions and environment.

FUTURE RESEARCH DIRECTIONS

With the rising cost of chemical fertilizers, and the ever increasing opposition to their use from an environmental point of view, more research will definitely need to be put into converting available biomass (both marine and terrestrial) into natural, low-cost, naturally obtained and sustainable soil additives such as those derived from marine algae. Aside from algal blooms, SIDS are facing issues with infestations of marine organisms such as the Crown of Thorn Starfish (COT), a predator of live corals with the potential to decimate entire areas of coral reefs in a very short time (Moran, 1988; Engelhardt & Lassig, 1992).

Biogas and fertilizer from marine algae

A proposal by the authors for a pilot project in Vanuatu and Tuvalu will explore the possibility of converting mixed seaweed and COT biomass to fertilizer and biogas. Ideally, we aim to develop a versatile anaerobic digestion method using low-cost, locally available materials that can cater for both marine biomass such as algae and COT, and terrestrial wastes such as pig and human manure and garden refuse, depending on respective supplies. There is a huge amount of excess biomass available, which at present is being disposed of in a less than well-managed manner; for instance some resorts in Fiji are collecting and barging away at high cost seaweed washed up on their beaches for disposal further out at sea, where they can wash back to land (Fig. 11). A much better use of this biomass would be conversion to biofuels and/or fertilizers for local communities. Algal and COT blooms are episodic, and planned reductions in the use of chemical fertilizers and better managed waste disposal systems in SIDS should hopefully reduce their occurrences in future, hence needing further research into increasingly diversified methods to reduce dependency on fossil fuels and chemicals for food security and energy needs.

Figure 11. Excess seaweed (*Gracilaria edulis*) collected from a resort in the Mamanucas, Fiji being carted away to sea on a barge (photo courtesy Dr. Luke Mosley, and used with permission).

Field trials to develop specific crop management profiles using seaweed fertilizer

Farmers in the Pacific region are faced with the dilemma of carrying out agriculture in poor sandy soils, often leached of nutrients and contaminated by saltwater intrusion, and at the same time been advised to avoid using chemical fertilizers rich in phosphates and nitrates that can harm the environment (Mosley & Aalbersberg, 2005; Grant *et al.*, 2006; Conley *et al.*, 2009). Moreover, large quantities of chemical fertilizer such as Nitrates are still being imported at high cost and used regularly in SIDS (Fig. 12). What is needed is a solution using low-cost, readily available materials, and marine excess biomass like algae and COT fulfill this need very adequately, as outlined in preceding sections of this chapter. We are hoping to continue research in this area, using controlled lab and field experiments on staple Pacific crops, using different management profiles based on marine biomass fertilizers. These postgraduate student-based research projects would focus on quick-maturing crops such as sweet potato, corn, long bean, cucumber and tomato. The ultimate aim would be to produce a best-practice guide that SIDS farmers could utilize to make the best use of the opportunities to fertilize their crops according to their local conditions and available biomass.

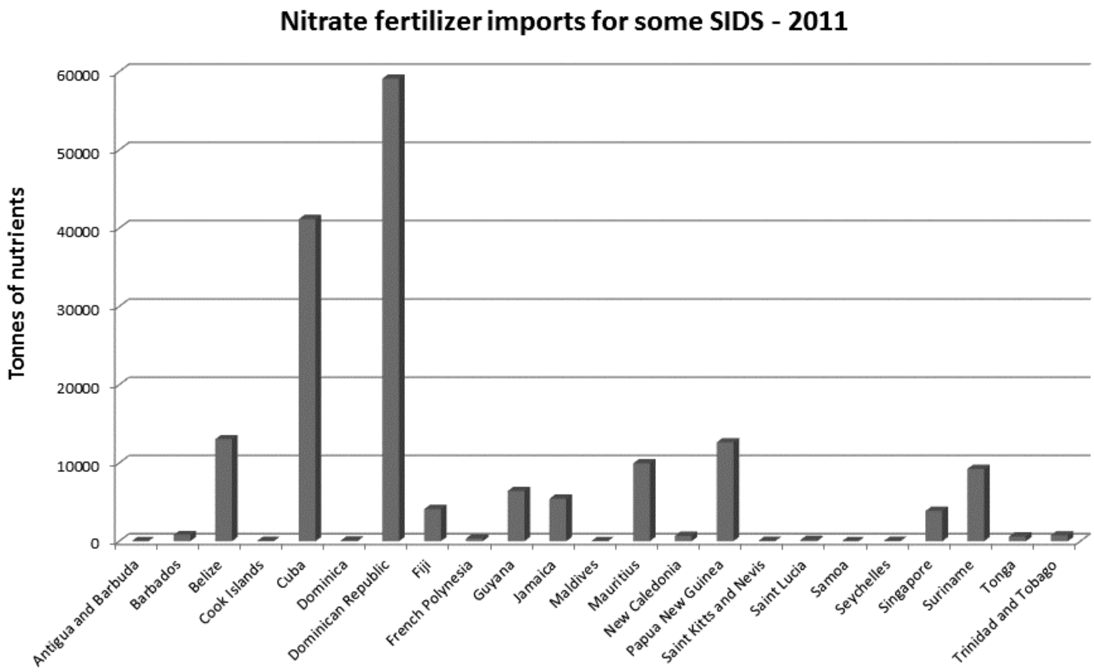

Figure 12. Imports of Nitrate fertlizers (in tonnes of nutrients) being imported by some SIDS in 2011 (data from FAO, retrieved on 3rd January 2014 from: http://faostat.fao.org).

CONCLUSIONS

With the looming threats of climate change, Pacific SIDS are finding themselves at the frontline of combatting the effect of such change on their shores and on their land. Sea-level rise is intensifying the effects of salt intrusion into the water table and arable land, while increased rainfall, stronger cyclones and hurricanes, flooding and deforestation all contribute to leaching of soil nutrients making agriculture a challenge, especially for low-lying atolls such as Tuvalu and Kiribati. The concomitant issue of seaweed blooms that affect island nations in recent years and which is fueled by overpopulation and poorly managed waste disposal and agricultural practices, could lend itself as a solution to the soil deficiency problem via conversion to fertilizer and biofuel, with the resultant synergy benefiting both the environment and the affected communities.

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